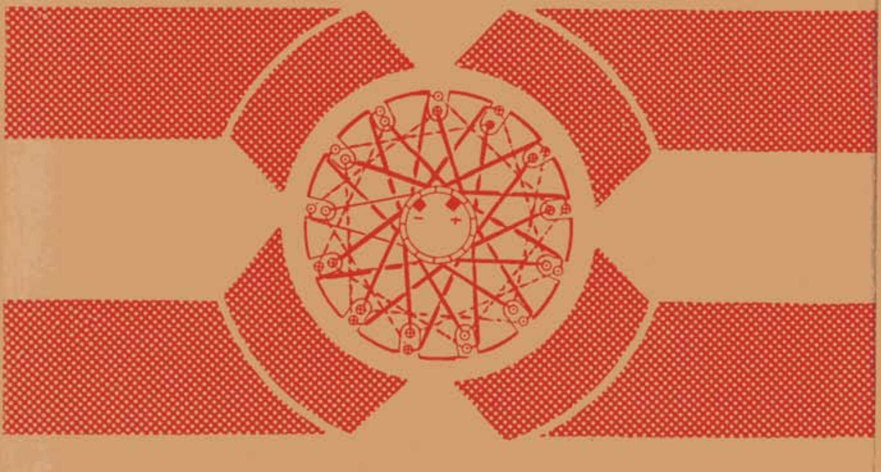
ARMATURE
and
MAGNET WINDING



HORSTMANN
and
TOUSLEY

Drake's Practical Books of Instruction

written and illustrated by men of PRACTICAL EXPERIENCE who are classed as AUTHORITIES in their particular fields.

Carpentry and Building

Carpentry (Craft Problems). Cloth	$2.00
Building—Forms, Stairs, Roofs. Cloth	2.00
Quick Construction (Building Problems). Cloth	2.00
A Practical Course in Roof Framing. Cloth	2.00
Wooden Boat and Ship Building. Cloth	2.00
The Steel Square. Cloth	2.00
A. B. C. of the Steel Square. Cloth	1.00
Modern Carpentry. Cloth	2.00
Modern Homecraft. Cloth	3.00

Painting—Decorating

Cyclopedia of Painting and Decorating. Cloth	$3.00
The Mixing of Colors and Paints. Cloth	2.00
Wood Finishing, Plain and Decorative. Cloth	2.00
Interior Wall Decoration. Cloth	3.00
House Painting Methods. Cloth	2.00
Practical Instruction for Paper Hanging. Cloth	2.00
Spray Painting, Industrial and Commercial. Cloth	1.50
Furniture Finishing, Decoration and Patching. Cloth	4.00
Estimating for Painters and Decorators. Cloth	2.00
Graining—Ancient and Modern. Cloth	3.00
New Stencils and Their Use. Cloth	1.50

Refrigeration-Air Conditioning-Plumbing

Drake's Refrigeration Service Manual. Cloth	$2.00
Heating, Cooling and Air Conditioning Handbook	4.00
Plumbing—Installation and Repair. Cloth	2.00

Mathematics

Slide Rule and Logarithmic Tables. Cloth	$1.50
Mathematics for Ready Reference. Cloth	2.00

If the above titles are not available at your dealers, write direct to the Publishers.

SEE OTHER JACKET FLAP FOR ADDITIONAL TITLES.

FREDERICK J. DRAKE & CO.
600-610 W. Van Buren St. Chicago 7, Ill., U.S.A.

ARMATURE AND MAGNET WINDING

HORSTMANN AND TOUSLEY

TECHNICAL BOOK & MAGAZINE CO.
297-299 SWANSTON ST.
OPP. OLD MELBOURNE HOSPITAL
CENT. 2041 MELBOURNE, C.1

PRACTICAL
ARMATURE AND MAGNET
WINDING

A Comprehensive Treatise for the Workers;
Fully Illustrating the Theoretical Principles and
Shop Practice of Armature and Magnet Work

By
HENRY C. HORSTMANN
and
VICTOR H. TOUSLEY
Consulting Electrical Engineers

ILLUSTRATED

CHICAGO
FREDERICK J. DRAKE & CO.
Publishers

COPYRIGHT 1941
BY
HENRY C. HORSTMANN
AND
VICTOR H. TOUSLEY

Printed in U. S. A.

PREFACE.

In this work an effort has been made to supply working electricians with a practical treatise on Armature and Magnet Winding. Special stress has been laid upon the practical side of the subject, so as to enable the student to see clearly the exact manner in which the work is actually performed.

Sufficient of the theory of armature winding has been given to enable the student to comprehend fully why certain precautions and methods are necessary. Without this theory an intelligent understanding of the necessity of complying with these conditions is impossible.

In this work, no less than in the others preceding, the motto of the authors has been: "Everything that is needed and nothing that is not needed."

The manner in which the previous efforts of the authors have been received by the practical workers in the electrical field gives rise to the hope that this volume may be of equal benefit to those interested in this particular line of work, and that it may so prove is the earnest wish of

THE AUTHORS.

TABLE OF CONTENTS

CHAPTER I.

ELEMENTS OF ARMATURE DESIGN.................. 1

CHAPTER II.

MECHANICAL CONSIDERATIONS 33

CHAPTER III.

ARMATURE WINDINGS—DIAGRAMS.................. 44

CHAPTER IV.

RING ARMATURES 103

CHAPTER V.

DRUM ARMATURES 118

CHAPTER VI.

COMMUTATOR CONSTRUCTION 134

CHAPTER VII.

ARMATURE TROUBLES 140

CHAPTER VIII.

ARMATURE CALCULATIONS 148

CHAPTER IX.

ALTERNATING CURRENT ARMATURES...............161

CHAPTER X.

MAGNET WINDING 189

CHAPTER XI.

USEFUL FORMULAS AND TABLES...................237

CHAPTER XII.

PLUNGER MAGNETS 257

CHAPTER I.

ELEMENTS OF ARMATURE DESIGN.

Current Generation.

Figures 1 and 2 are drawn to illustrate the principles of current generation in dynamo armatures. Figure 1 shows the simplest possible form of dynamo; the armature consists of but one turn of wire, as shown by heavy black lines. This wire is assumed to be fastened to the shaft and to turn with it in the direction of motion, in this case indicated by the arrow. In the dynamo, it is well known that an E. M. F. is generated by a conductor cutting lines of force; the current, in turn, depends on the E. M. F. so produced. The E. M. F. depends on the rate at which the lines of force are cut, i. e., upon the number cut in a given time. To produce one volt it is necessary to cut lines of force at the rate of 100,000,000 per second. It is immaterial, so far as the generation of this voltage is concerned, whether one wire cuts through a field containing 100,000,000 lines of force once per second, or whether one wire passes through a field containing 10,000 lines of force, for instance, 10,000 times per second.

If the shaft of the armature, Figure 1, be set in motion, the wire revolves with it and begins to cut lines of force, shown as broken lines in Figure 2. The direction of flow of the current generated in the wire depends upon the direction of the motion of the conductor and the direction of the lines of force being cut. A reversal of either of these two factors will effect a reversal of the current; if both are reversed, there will be no change. A very handy rule by which these various factors may be kept in mind has been given by Fleming and is as follows: Place the thumb and first two fingers of the right hand in a position at right angles to each other as shown in Figure 3. Assuming that the lines of force pass from the north to the south pole, place the hand in such a position that the index finger will point in the direction of the lines of force. If the thumb now points in the direction of motion of the conductor, the second or middle finger will

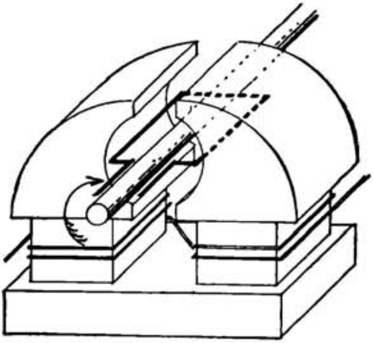


Figure 1.

indicate the direction of flow of the induced current. For determining these directions in the case of a motor, use the left hand in a similar manner.

If we notice closely the conductor, Figure 2, through the course of one revolution, we shall see that with every half revolution the direction of current within it must change; for the wire at the right, moving downward, cuts the lines of force in just the opposite direction to what it will when it arrives at the lower position and begins to move upward. The same change will, of course, take place in the other half of the wire shown at the left. In Figure 2 the direction of flow of the current in the conductor is indicated by the conventional signs, a dot rep-

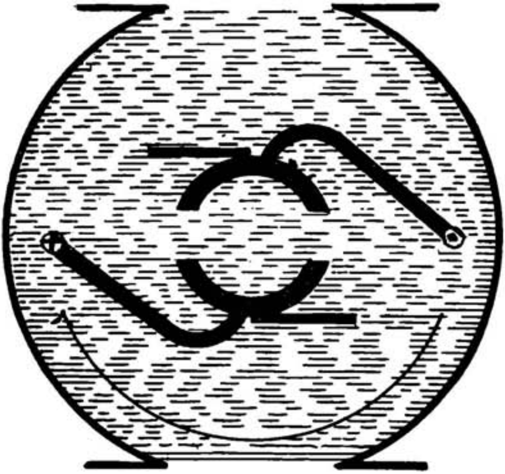


Figure 2.

resenting current flowing toward the observer and a cross representing current flowing away from the observer. These two symbols may be easily remembered by considering the dot as the advancing point of an arrow and the cross the retreating tail feathers.

There are two different ways in which the current in the revolving conductor can be collected, and which of these ways we choose to use determines whether we shall receive an alternating or direct current from the dynamo. If we select the method shown in Figure 4 we shall obtain an alternating current; that is, a current which will be reversed in direction every half revolution of the armature. Not only will this current change in direction, but it will also continually change in strength. We have already stated that the E. M. F. produced varies with the rate of cutting lines of force. Since the speed

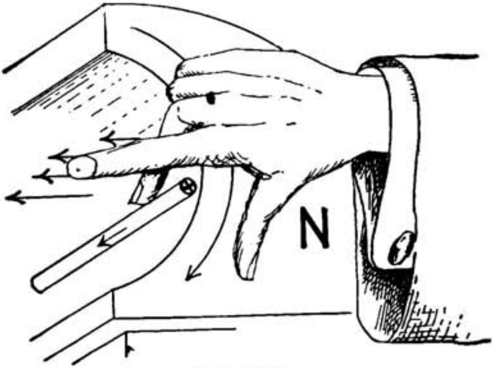


Figure 3.

of the wire is of necessity uniform, it is apparent that it will be cutting lines of force at the highest rate of speed while in the position shown in Fig. 2, i. e., at right angles to the lines of force. As the wire leaves this position it moves, more and more, in a direction parallel to the lines of force until it assumes a vertical position. At this point it is moving exactly parallel to the lines of force and is generating practically no current. The current has fallen to zero, but an instant later it will again begin to increase in value, but in the opposite direction, continuing in this direction until the wire again assumes the vertical position, when the current again sinks to zero only to reverse again immediately after.

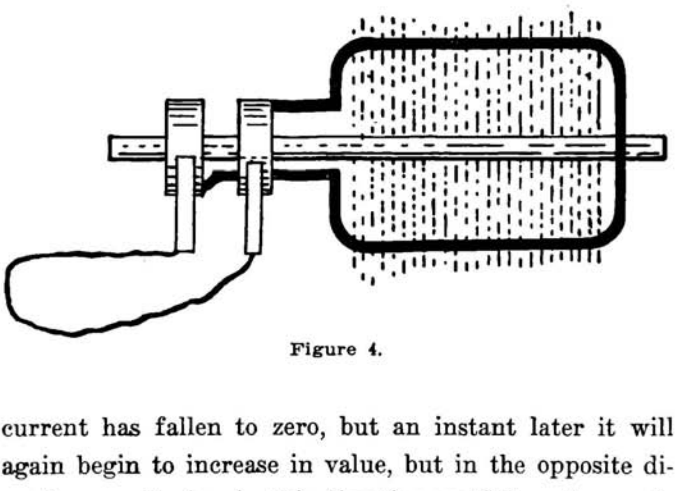


Figure 4.

For very many purposes the alternating current is not desirable and it therefore becomes necessary to rectify it. In order to do this the wire is connected as shown in

Fig. 5. While in Fig. 4 we had only two collector rings which served simply to make connection with the armature conductors and the outside circuit, in this figure we have what is termed a "commutator." The office of this commutator is to change the connections between the armature wires and the outside circuit at the proper moment in such a manner that the current in the outside circuit may be always in the same direction. This is done in the following manner: Referring to Fig. 2 it will be noticed that there are two brushes resting upon the commutator and that these brushes serve to take off the current and deliver it to the external circuit. The commutator as it revolves with the shaft slides under these brushes, and when the wires assume a vertical position the opening between the two halves of the commutator will be in a line with it and both halves will be in contact with each of the brushes. At this point the

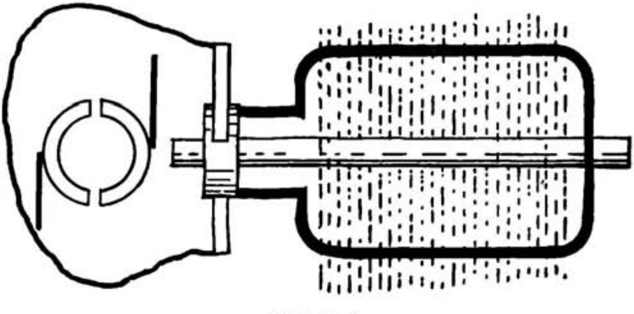


Figure 5.

coil will be short-circuited. As the wire continues in motion, a moment later the upper conductor will have changed from connection with the lower brush to that of the upper brush with a corresponding change in the lower conductor. It will be further noticed that this change was made to occur at just the time when no current was being generated. It can further readily be seen that with this arrangement the current in the outside wires remains always in the same direction, while, in the armature itself it continues to alternate as before.

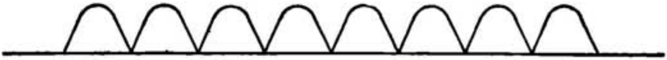


Figure 6.

A simple dynamo, the armature of which consists of but one turn of wire, is of course impracticable. Every actual dynamo has a large number of turns of wire in order to procure the requisite E. M. F. If, however, instead of the one turn we should place a hundred turns of wire on the armature in the same manner, by taking that many turns around the core before connecting the other end to the commutator, we would still have a dynamo that, while it would operate, would be of very little use. A dynamo having but one coil would deliver a current that would be constantly fluctuating in value as represented by the curve in Fig. 6. The current, although always in the same direction in the external circuit, would drop to zero every time the coil would come to that part of the field where the lines of force cut are parallel to the motion of the conductor. This coil would also, owing to its width, be short-circuited by the brushes while some of the conductors were in the active field and considerable sparking would be apt to result.

By adding another coil to the armature at right angles to the coil shown we would have a commutator consisting of four segments. Only one coil at a time would, therefore, be short-circuited, and while one coil was generating practically no current, the other would be generating its maximum current. This current may be represented by the curve, Fig. 7, where it will be seen that

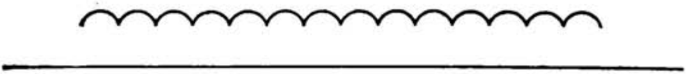


Figure 7.

the irregularities in the current strength are somewhat reduced, the current approaching a more uniform value. It is evident that by increasing the number of coils and placing them at regular distances around the armature these irregularities would be still further decreased. For this reason, and for a number of others of which we shall treat more fully in another chapter, armatures are always provided with a large number of coils.

If we were to reverse the conditions just described and instead of turning the armature and taking current from it we were to have a current flow through it in the opposite direction, as would, for instance, be the case where two dynamos are operating in parallel and the belt should slip off of one, the conditions would be as shown in Fig. 8. The current passing around the armature in the conductors tends to set up poles, as indicated by the vertical line drawn through the center of the figure. The poles set up by the armature and those of the fields act upon each other. A north pole attracts a south pole and repels another north pole, hence the armature is drawn around as indicated and continues to move in the same direction.

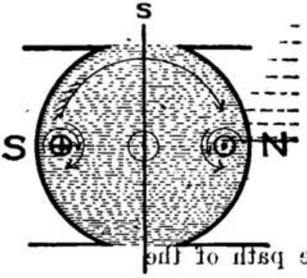


Figure 8.

ARMATURE REACTION.

The armature always revolves within a magnetic field as depicted in the preceding figures and the lines of force must pass through it in order that it may generate the necessary potential. If the fields were so magnetized as to produce north and south poles, as shown in Fig. 9, an iron armature core placed between these pole pieces would then be magnetized with opposing poles, as shown in the figure. When the armature begins to deliver current, however, it also becomes an electro-magnet and sets up a field of its own. If the brushes were set so that current flowed through the armature conductors as shown in Fig. 10 the armature would then become a magnet with north and south poles as shown. This figure shows a ring armature with the front end of the conductors removed so as to give a view of the iron core and admit

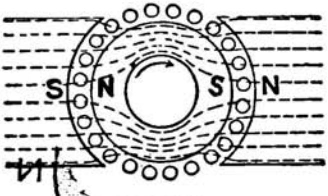


Figure 9.

of showing the path of the lines of force. When this armature is generating current the flow is away from the observer in those wires shown with crosses and toward the observer in those wires shown with dots. The outgoing currents from the two sides meet at the top and the entering current from the external circuit divides at the bottom, half passing through each side of the armature.

If this magnetized armature were now placed between the pole pieces shown in Fig. 11 an entirely new field.

the resultant of the field produced by the pole pieces and the field produced by the current in the armature, would be set up. The conditions as they would then exist are shown in Fig. 11. The north and south poles of the armature now occupy an oblique position between the two previous positions (that due to the field magnets and that due to the armature currents). If very little current flows in the armature conductors it is quite evident that the armature polarity will be due almost entirely to the field magnetism, or as shown in Fig. 9. As the current in the armature increases the armature poles will gradually shift their positions (assuming the field magnetism to remain constant) and their position will, at any time, depend on the current flowing through the armature.

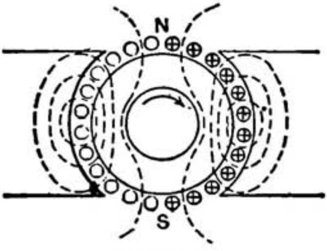


Figure 10.

In order to obtain sparkless commutation it is necessary, as will be more fully explained in the following pages, that the brushes rest on the neutral point, or that point at which the armature conductors are moving parallel to the lines of force, and where, consequently, there can be no generation of current. This position will be at right angles to the line between the armature poles. If the armature is delivering very little current the neutral line will lie approximately midway between the pole pieces, while, if the armature is delivering considerable current, there is a greater reaction and the armature poles, and likewise the neutral point, will shift its position in the direction of rotation of the armature. It can readily be seen that as the neutral point is shifted the tendency of the armature current is to still further distort the resultant field. Thus it becomes necessary to shift the brushes in the direction of motion of the armature with an increased load, and in the opposite direction with a decreasing load.

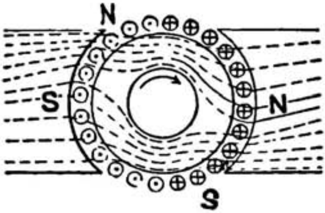


Figure 11.

This effect is known as the "cross magnetization" of the armature, due to the cross field or field at practically right angles set up by the armature currents. This reaction is much greater in a ring armature than with a drum armature and is one of the reasons why such armatures are better suited for variable voltage arc circuits than the drum armatures. At the same time this fact makes the armature less suitable for constant potential work.

It will be specially noticed that the lines of force are crowded together at the ends of the pole pieces from which the armature is receding. The relation between the direction of the lines of force and the motion of the conductor will always exist in the case of a dynamo, and hence it can be seen that the lines at the top resist, and those at the bottom assist, the flow of the lines of force in the field. This effect must be taken into consideration in the design of an armature, as the permeability of the iron may be considerably reduced by the excessive number of lines of force passing through the pole tips.

In the case of a motor the current in the armature is in the reverse direction to that of a dynamo. The same distortion of field will result, but in this case the armature will have a polarity opposite to that shown in Fig. 11. The lines of force are now crowded together at the pole tip toward which the armature is advancing, or against the direction of rotation. The neutral line of the armature is also shifted in the opposite direction and the brushes must, therefore, be moved correspondingly.

DEMAGNETIZING EFFECT OF THE ARMATURE.

When an armature is revolving between the pole pieces of a field magnet and is generating only a small current, the brushes occupy a position practically midway between the pole pieces and the only effect the armature currents would have on the pole pieces would be that due to the cross magnetization. When a considerable current is being generated in the armature and the neutral point has been shifted and occupies an oblique position, the armature currents will be seen to influence the field magnetization in another way This effect may be seen by re-

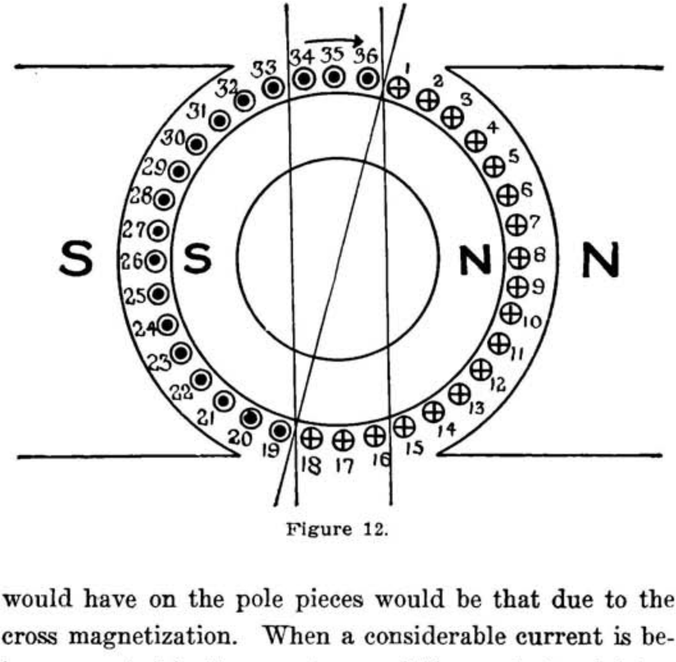


Figure 12.

ferring to Fig. 12. Here the brushes have been shifted to the position of sparkless commutation. Tracing out the current in the armature conductors according to Fleming's rule it will be seen that current in conductors 1 to 18 flows toward the rear of the armature, and in conductors 19 to 36 toward the front of the armature. The current in conductors 1 to 15 and 19 to 33 tends to cross magnetize the magnetic field produced by the pole pieces, but the current in conductors 34 to 36 and 16 to 18 tends to produce north and south poles as indicated in the figure. These poles are in opposition to the field poles and tend to demagnetize them. Those armature conductors, therefore, which lie between the two upright lines are known as the "demagnetizing" turns of the armature and they must always be considered in the design of a dynamo or motor, as the fields must be made strong enough to overcome their effect.

Fig. 13 shows the effects in the case of a motor. Here the current in the armature is in the opposite direction and the brushes are shifted against the direction of rotation. It will be seen that the demagnetizing effect is the same as in the case of a dynamo. It is possible to so design the armature and fields that in this way the magnetism of the armature can overpower the fields. The reaction of the armature can be decreased by increasing the air gap between the fields and the armature. Also, by increasing the strength of the fields, we are enabled to get along with a lower speed or fewer wires, and, as the reaction is proportional, other things being equal, to the ampere turns on the armature, it is thereby reduced. The greatest reduction in reaction, however, is effected when dynamos are constructed multipolar or with a number of poles.

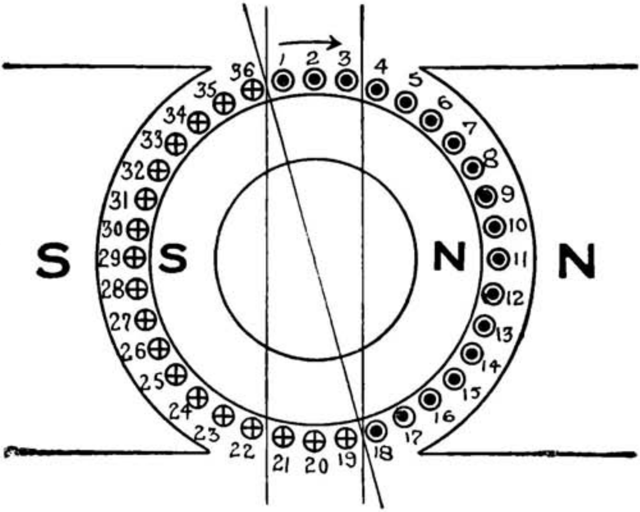


Figure 13.

SPARKING.

It is evident, from what has been said before, that to obtain sparkless commutation the brushes should be set at approximately the neutral point, this being the point toward which the current generated in the two halves of the armature tends to flow. This position is shown for an armature generating heavy current in Fig. 14, where only a section of the armature with the commutator segments and conductors approaching a south pole piece are shown. Tracing out the induced currents, it will be seen that current in conductors 1 and 2 of the left-hand half of the armature are flowing around the iron ring core toward commutator segment *c*, upon which the brush rests. Current in conductors 3 and 4, etc., which belong to the right-hand half of the armature, is flowing in a reverse direction around the core, also toward the commutator segment *c*. It is apparent that when conductor 2 passes the neutral point, the current in this conductor must be reversed.

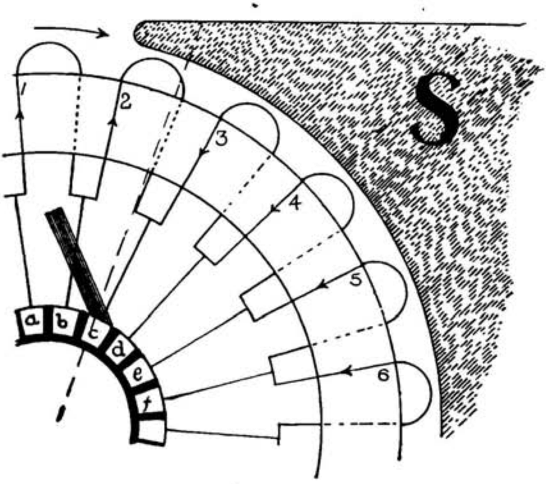


Figure 14.

Every coil has a certain inductance; that is, it tends to restrict any change in the current passing through it. If, when there is no current passing through it, the coil was connected to a live circuit it would take some little time for the current to reach its full strength. On the other hand, if current is already passing through the coil and the circuit is suddenly broken, the current tends to keep on flowing and manifests itself in the form of a spark. The greater the number of turns comprising the coil and the better the quality of the iron of which the core is constructed, the greater the inductance.

As the armature moves to the right, the brush will make contact with commutator segments *b* and *c*, and coil 2 will be short-circuited. Two things may now occur. If the brush happens to be set a little to the left of the neutral point, coil 2 will be in a position where it is cutting lines of force and generating current. If the resistance of the coil is low, as it generally is, considerable current will be generated, and this current will flow in the same direction as previously, but only in the coil instead of the circuit.

If the brush is set a little to the right of the neutral point, coil 2 will again be in a position where it will cut lines of force, but the induced current will tend to flow in a direction opposite to that previously flowing in the coil.

As the armature continues to revolve, commutator segment *c* leaves the brush and coil 2 is then thrown in series with the balance of the coils on the right-hand side of the armature. With the brush in the position as given in the first case, coil 2 would be generating considerable current in the same direction as that in coil 1 and the current from coil 3, being opposed by that in coil 2, would then jump across the space between the commutator segment and the tip of the retreating brush and severe arcing would ensue, this arcing continuing until the opposition offered by coil 2 had been reduced to a sufficient extent to allow the current to flow through it.

If, at the moment of separation, between the brush and the segment *c*, the brush was in the second position described, or at the right of the neutral line, the current in coil 2 would have been reversed at the time of breaking contact with the segment and would have been flowing in the same direction as that in coil 3. This coil would therefore offer no resistance to the passage of current through it from the remaining coils on the right-hand side of the armature and no arcing would occur at the time of separation of the brush and segment.

It is apparent that there will be one position where the brush can be set and at which no detrimental arcing can occur.

The bearing surface of the brush also has an effect on the sparking. With a brush just wide enough to cover the insulating space between the segments the current in coil 2 would have to be reversed instantly at the point of break to avoid sparking. This, of course, could not be done. If the brush was carried to the other extreme and made large enough to cover several segments, several coils would be short-circuited for some length of time, and the armature, commutator and brushes would become heated from the excessive current. This would also cut down the voltage produced by the machine, as several coils would be inactive.

The sparking of a dynamo is also greatly affected by the resistance of the brushes. An inspection of the figures will show that the current which is generated in a coil while it is on short circuit must pass through both lead wires and the brush. In an armature of many coils the E. M. F. produced in any coil is quite small and hence a little resistance will considerably check it. Furthermore, the greater the current used by the machine the less will be the tendency of the current generated in the coil to flow in opposition to the current in the main circuit. The coil should therefore be in such a position that the current induced in it tends to oppose the current in the main circuit which enters or leaves the brush.

Another effect that must not be overlooked is the reduction of the E. M. F. by an improper position of the brushes. If the brushes are shifted too far, many of the coils on the same side as the brushes will be in fields of opposite sign, *i. e.*, generating E. M. F. in opposite directions, and will therefore neutralize each other. If the reaction of the armature is very great it will destroy the opposing field ahead of the coils, as can be seen from

Fig. 11; that is, the lines of force of the fields will be partly overcome by the countermagnetization of the armature and the coils spoken of will merely be dead or inactive. But if the reaction of the armature is small the field will remain undisturbed and some of the coils will act in opposition to each other.

MAGNETIC CIRCUIT.

If an ordinary bar magnet is placed directly below a sheet of cardboard, upon which has been sprinkled a small quantity of iron filings, and the cardboard is then gently tapped, the filings will align themselves in the position shown in Fig. 15. The position of these filings indicate the presence of a magnetic field in the space surrounding the magnet.

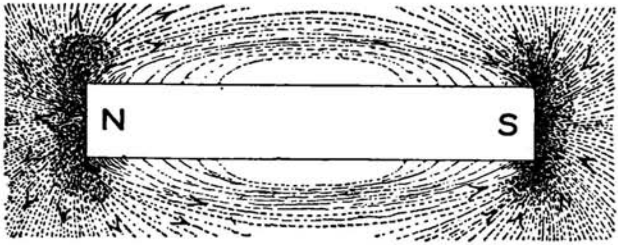


Figure 15.

Every magnet is supposed to be surrounded by a field similar to the one shown, this field being traversed by magnetic lines which pass through the metal of the magnet, pass out of the magnet at one end and return through the space surrounding the magnet and enter it at the other end, thus making a complete circuit. Whether or not these magnetic lines actually exist we do not know; for our purpose we are more concerned in the effects of these magnetic lines than in their actual existence, and the assumption of a magnetic field with magnetic lines gives us a convenient method for understanding and explaining the various actions. It is also assumed that in a magnetic circuit the lines of force flow through the air from a north pole to a south pole.

If the permanent bar magnet in Fig. 15 was replaced by a coil of wire carrying a current of electricity, practically the same effects would be observed as in the case of a permanent magnet.

A permanent magnet is composed of a large number of molecules, each molecule forming by itself an individual magnet with north and south poles. When these molecules become united and form a homogeneous mass the magnetism of all of them unites and forms one magnet with north and south poles. In a similar manner each turn of wire in a coil sets up a magnetic field of its own, but when a number of turns are combined to form a coil the magnetic effects of all of the turns unite and form one magnetic field with north and south poles.

The force which sets up the magnetic field is known as the "magneto-motive force," just as the force which induces a current of electricity to flow is known as the electro-motive force. The two forces in their actions are entirely similar. In an electrical circuit the effective E. M. F. is a combination of all the individual E. M. F.'s; for instance, the effective E. M. F. in a battery circuit is the combined E. M. F.'s of all the batteries in the circuit. So it is in the case of a magnetic circuit, the magneto-motive force (M. M. F.) which is effective in producing the magnetic lines is the combined magneto-motive forces of all the individual elements.

The magneto-motive force in an electro-magnet or solenoid depends upon two things: First, the amount of current passing through the wire of the coil, and second, the number of times the wire encircles the core, or, taking these two things together, the ampere turns. The effect is independent of the size, shape or composition of the wire (except, of course, as these may affect the current), or of the manner in which the turns are placed upon the core. It is also immaterial, so far as the resultant flux is concerned, what proportion exists between the number of turns and the amperes. For example: 25 turns of wire carrying 4 amperes would give the same results as 4 turns of wire carrying 25 amperes, the ampere turns in each case being 100.

If we were to pass a steady current through the wire of a coil we would find that a magnetic field would be produced. If we measured the strength of this field we would find a certain definite number of lines of force to each unit of area, the exact number depending on the magneto-motive force producing the field. If an iron core is placed inside of the coil and the number of magnetic lines per unit of area again ascertained it would be found that the number had greatly increased. This increase in the number of magnetic lines is the result of decreasing the resistance of the magnetic circuit. Just as every substance offers a certain resistance to the flow of an electric current, in a like manner every substance offers a certain resistance to the flow of magnetic lines. In the case of a magnetic circuit this resistance is called the "reluctance." Reluctance in a magnetic circuit and resistance in an electrical circuit are analagous with these exceptions: With a uniform temperature the resistance of an electrical conductor is independent of the amount of current flowing. In a magnetic conductor the reluctance varies and bears a certain relation to the number of magnetic lines present, or the magnetic flux.

The magnetic flux is inversely proportional to the reluctance, but is directly proportional to the permeability, the permeability being the reciprocal of the reluctance. In comparing electrical conductors we generally consider their conductivities, the conductivity being the reciprocal of the resistance; for instance, if a certain conductor has a resistance of 2 ohms and another conductor of the same length has a resistance of 4 ohms, their conductivities are as ½ (.5) is to ¼ (.25), or in other words, the conductivity of the first is twice the conductivity of the second.

The same relation holds true with permeability in a magnetic circuit; the higher the permeability, the greater the number of magnetic lines produced with a given magnetizing force. The permeability of air is considered as unity. The permeability of any other substance is the ratio between the number of lines of force produced with a given magnetizing power when the magnetic circuit is composed of the substance in question and when it is composed of air.

If a coil of wire comprising a certain number of ampere turns produced 20 lines of force per unit area in air and 2,000 magnetic lines when an iron core was used, the permeability of the iron core would be 2,000/20, or 100.

The permeability of the iron, as has already been stated, varies according to the degree of saturation. If we were to magnetize a piece of iron to a low degree by allowing a small current to flow through the wire of the coil surrounding it, we would find a certain number of lines to be produced in the iron core. If, by gradual steps, we increased the magnetizing current and at each step determined the number of lines produced, we would notice that the resulting magnetism would at first increase in about the same proportion as we increased our magnetizing current. After a certain point was reached the iron would become saturated and an increase in the exciting current would cause very little increase in the magnetic lines. The permeability is, therefore, higher when the iron is only slightly magnetized and lower when we approach saturation.

The curves, Fig. 16, show the behavior of several metals under various magnetizing forces. The ampere turns per inch are plotted along the horizontal line and the resulting magnetic lines per square inch along the vertical lines. An examination of the curves will show that, in the case of wrought iron, for instance, when the metal is first magnetized, a certain number of magnetic lines will be produced per square inch. As we increase the magnetizing current we find that the resulting magnetism increases very rapidly until we arrive at the point where the metal approaches saturation. Beyond this point an increase in the ampere turns results in only a slight increase in the magnetic lines.

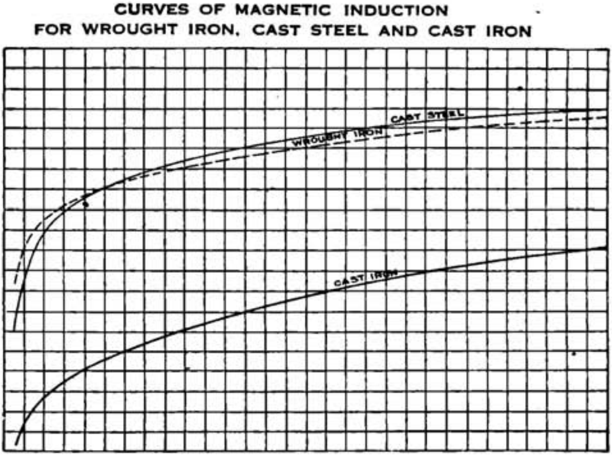

CURVES OF MAGNETIC INDUCTION
FOR WROUGHT IRON, CAST STEEL AND CAST IRON

Figure 16.

In designing an electro-magnet of any kind, such as the field coils of a dynamo, for instance, this peculiarity of the iron must be taken into consideration and it would, generally, be inadvisable to work the iron much beyond the point where it reaches saturation.

With cast iron it will be seen that a given magnetizing force produces a much smaller magnetic flux density than with wrought iron. It is usual in the design of magnets to ascertain the exact behavior of the iron which it is intended to use so that its exact action under various magnetizing forces is known.

In an electrical circuit, by insulating the conductors or surrounding them with materials of high resistance, we may confine the flow of current to certain definite paths. This cannot be done with a magnetic circuit, as there is no known insulator for magnetic lines of force. This can be seen by the location of the filings in Fig. 15.

The lines of force leave the magnet over its entire length and are not confined entirely within the metal. Outside of iron and the magnetic metals all materials such as air, wood, brass, etc., possess the same reluctance and, so far as the effects shown in Fig. 15 are concerned, they would be identical were the magnet surrounded by any of these materials. While it is impossible to insulate the path of the magnetic lines, we may by providing paths of low resistance confine them to certain definite directions.

The reluctance of a magnetic circuit increases directly with the length and inversely with the cross section, just as the resistance of an electrical conductor increases with its length and decreases with its cross section. As an example, doubling the length of a magnetic circuit doubles the reluctance and doubling the cross section halves the reluctance.

Taking into consideration the several properties of the magnetic circuit just described, it has probably already been seen that the principles of Ohms law as applied to electrical circuits will also apply to the magnetic circuit. For the electrical circuit Ohms law is:

$$\text{Amperes} = \frac{\text{Electro-motive force}}{\text{Resistance}}$$

For the magnetic circuit this law would apply:

$$\text{Magnetic flux} = \frac{\text{Magneto-motive force}}{\text{Reluctance}}$$

Fig. 17 shows the magnetic circuit in a bi-polar dynamo. The magneto-motive force is supplied by the windings on the two field magnets. The reluctance of the magnetic circuit is determined by the composition of the metal of the frame and armature, the length and cross-section of the several parts of the magnetic circuit, the joints in the metal frame and the air gap on either side of the armature. The magnetic flux, therefore, is the result of these factors and it can be increased by increasing the exciting turns, which will increase the magneto-motive force, or by decreasing the reluctance by providing a suitable metal, or by increasing the cross-section of the magnetic path or by decreasing the loss due to the mechanical joints and the air gaps.

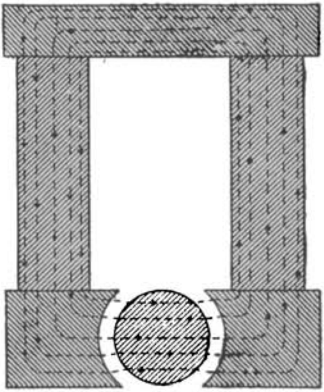


Figure 17.

FOUCAULT CURRENTS.

We have seen how an E. M. F. is induced in a wire moving in a magnetic field. Such induction takes place not only in the conductors wound upon the core, but within the iron of the core itself. If an armature made up of a solid piece of iron is revolved in a magnetic field, as shown in Fig. 18, currents of electricity will circulate in the iron as indicated by the broken lines and arrow heads. If the speed of the armature be very great these currents will be of considerable strength and will heat the iron and consume energy. Such currents can never be entirely prevented, but they can be reduced to a minimum by laminating the core. Instead of the armature being made up of one solid iron core, it is made up of a number of thin plates of the proper dimensions. These plates are usually 1/100 to 1/25 of an inch thick. They are pressed together after first having been insulated from each other either by the oxide which forms on the surface of the iron, or by sheets of paper or suitable varnish. These plates or punchings are put on the armature shaft so that they lie in a line with the lines of force and at right angles to the direction in which the induced currents would flow. In an armature made up in this manner the induced currents can circulate only in the individual disks, and, if these are thin, these currents will amount to but very little.

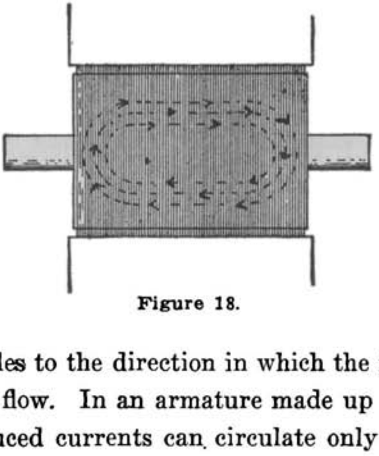


Figure 18.

These eddy currents are also produced in the pole pieces owing to the variation in the magnetic field which occurs when the armature rotates. Especially is this the case with slotted armatures.

HYSTERISIS.

This is another of the troublesome factors in armature construction. Iron, in general, has the property of retaining some of its magnetism; that is, when the magnetizing force is withdrawn not all the magnetism leaves the iron. The remaining magnetism must be destroyed when a current in the opposite direction is set up around the coil. Where the magnetizing force is always in the same direction hysterisis does no harm; but, if the magnetism is rapidly reversing, its effects are quite noticeable. An inspection of Fig. 19 will show us the effects hysterisis has upon an armature. Since the lines of force move from a north pole to a south pole, the relative polarity of the fields and armature will be, at any instant, as indicated. But the armature is in constant motion; therefore the polarity of any given part of the iron of which the core is constructed will be constantly changing from one polarity to the other. If the iron is of

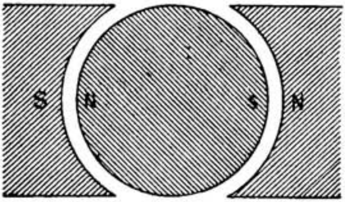


Figure 19.

such a quality that it retains a large amount of magnetism it will heat up considerably, and, since the number of reversals of the magnetism are in proportion to the number of revolutions, the greater the speed the greater will be the effect of hysterisis. To reduce the troubles from hysterisis to a minimum it is necessary to use a very soft annealed iron or steel.

CHAPTER II.

ARMATURES—MECHANICAL CONSIDERATIONS.

Economy of construction demands that an armature be run at a high rate of speed. In any armature the output in volts can be increased by simply increasing the speed; the output in amperes cannot be so increased unless at the same time larger wires are used. If, however, in any armature we should increase the size of the wires so that fewer turns would be upon it we can compensate for the consequent loss in voltage by increasing the speed and this, with the same armature, also increases the output in amperes. It will be seen that speed is an important item in the construction of any armature. To operate at a high rate of speed requires the very best workmanship and mechanical construction.

Whenever a high speed is to be used it is of the utmost importance to see that the armature is well balanced. Any rotating piece of machinery is said to be out of balance when one side is heavier than the other. This condition of being out of balance will manifest itself by a more or less severe jarring and shaking of the frame upon which it rests when running.

Whether an armature is in balance while at rest can be easily determined by placing it upon two knife edges, as shown in Fig. 20. If these edges are perfectly level the armature will roll to one side or the other until the heaviest part is at the bottom. If the diameter of the armature is small compared to its length this test will not be very sensitive. If the diameter is great as compared to its length a small excess of weight on one side will cause it to roll over. If a very good balance for high speed is to be obtained this method must not be relied upon. In such a case the armature should be placed in bearings and run at its proper speed. If there is much jarring or shaking the armature is out of balance and this must be rectified.

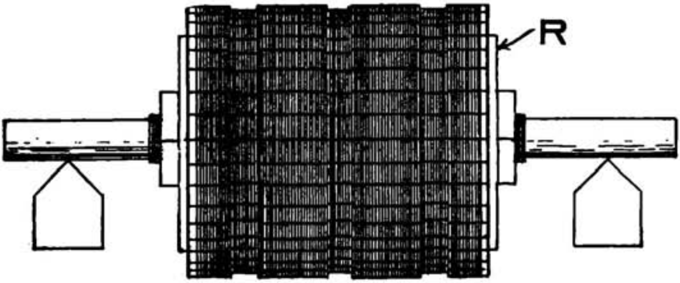


Figure 20.

It is obvious that this had best be done before any wire is placed on the core. How it may come about that the armature may be perfectly balanced statically and yet almost unfit for the work while in operation at a high rate of speed can be seen from Fig. 21. If there is an excess of weight at 1 this may be perfectly balanced for a state of rest by the addition of a similar weight at 2. If, however, the armature is revolved at a high rate of speed there will be a tendency to strain the shaft as indicated by the dotted lines.

An armature out of balance is rectified by adding weights at different places until the proper amount is found. This will make itself evident by the smooth running. If possible the weights should now be removed

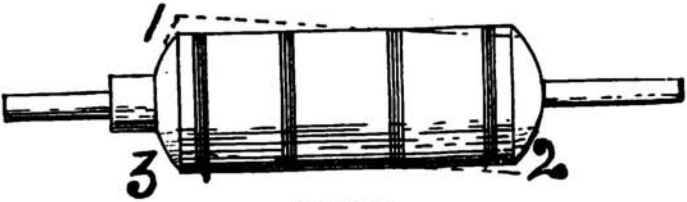


Figure 21.

and an equal weight of metal removed from the armature at the side opposite to that at which it was found necessary to add weight. If, for instance, it was found necessary to add one pound at 3, Fig. 21, the same result can be obtained by removing one pound at 1.

In speaking of high speeds it must be understood that it is not, necessarily, a great number of revolutions that are required to produce a certain E. M. F. What is required is that a certain number of conductors shall cut through the lines of force surrounding the pole pieces in a given length of time. As these conductors are always located on the periphery of the armature, it is the speed of this part that counts. The greater the diameter of the armature, therefore, the lower the speed of the shaft. Other things being equal, the capacity of an armature is directly proportional to its length. We may therefore choose whether we shall increase the capacity of a machine by increasing the length of the armature or the diameter.

If the length of the armature is too great there is some danger that the shaft will bend, not only from centrifugal force to which it is subject, but also from the magnetic attraction of the pole pieces if it is not well centered. For this reason armature shafts are often made as shown in Fig. 22.

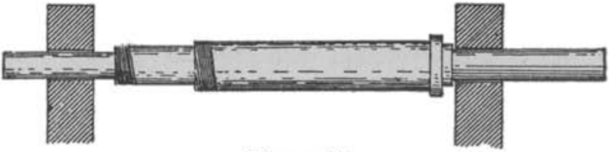


Figure 22.

The centering of an armature is an important point. It rests between two powerful magnets. If it is exactly in the center the attraction of one pole piece will neutralize that of the other, but if it is the least bit out of center there will be a strong attraction to one side and this will greatly add to the friction. The bearings and pole pieces should be in such relation to each other that the armature can be truly centered and that there will be no likelihood of their becoming loosened. The bearings should have sufficient surface so that the wear will be a minimum for wear will quickly bring an armature out of the center. Bearings should, furthermore, not be of iron or steel. If the shaft is constructed of the same material there may be some magnetic attraction between the shaft and the bearing which would increase the friction and cause heating. Bearings should also be out of line of the magnetic circuit, as such magnetization will cause the shaft to generate foucault currents which will heat it and in turn heat the bearings. The shaft should also be protected by shields which will prevent oil from running along it and getting into the wires on the armature. The lateral play which is essential to the smooth running of the shaft can be obtained by lining up the shaft after the belt is put on. This lateral play also tends to distribute the wearing surface of the brushes over the surface of the commutator, thereby giving a more uniform contact surface. It is quite evident that if the armature was made to run without this lateral movement the brushes would always bear on the same part of the commutator and a ridge would soon be worn in it.

The inexperienced mechanic should be warned not to skip lightly over any part of the work. While, of course, there is no visible connection between the armature and the pole pieces of the machine, and while it seems to be turning free and easy, it must be borne in mind that the force exerted upon the armature is, nevertheless, just as great as though a friction clutch of the capacity of the armature were applied to the periphery of the armature. Furthermore, in the case of a sudden overload or short circuit, or too rapid starting in the case of a motor, the force applied is almost as severe as the blow of a hammer.

MECHANICAL CONSTRUCTION OF THE ARMATURE.

All good armatures are made up of a number of punchings similar to those shown in Figure 23. These punchings are made of soft iron or steel. The figures illustrate the different forms of slots used in connection with armatures. Into these slots the wires are wound as will be hereafter explained. The punchings are usually made of thin iron with some form of insulation provided between them to reduce the foucault currents. This insulation is obtained by inserting layers of thin paper between the sheets of metal or by coating the punchings themselves. Paper and similar materials used for this purpose will in time char from the heat of the armature and work

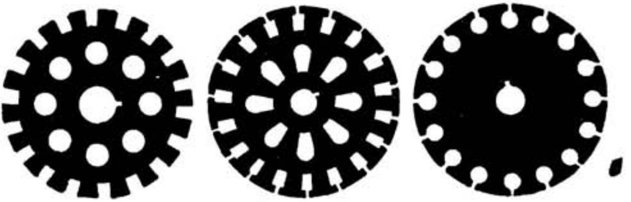


Figure 23.

out and tend to loosen the armature. Care should also be exercised in the use of an insulating varnish, as some of these varnishes will soften from the heat of the armature and are thrown out on the pole pieces.

As many of the punchings as are necessary are slipped upon the shaft of the armature as indicated in Figure 20 and fastenened together with clamps shrunk upon the shaft or with large nuts screwed on the shaft. Bolts extending through the punchings are often used. These bolts must be insulated from the punchings, otherwise there will be a flow of current through the shaft, the body of the armature and the bolts. (See Figure 24.) It is well to remember that in laying out the armature and the means of fastening it to the shaft that the foucault currents will flow according to the principles of any other electrical circuit so that to keep these cur-

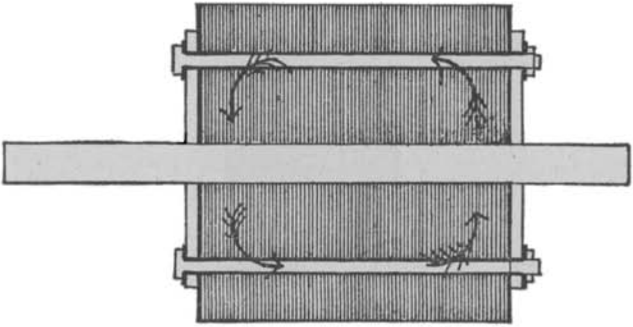


Figure 24.

rents to a minimum no electrical paths should be provided through the armature.

Where an armature is slotted as indicated in Figure 23 some of the punchings are often made of smaller diameter than the rest, or are afterwards turned down as indicated in Figure 20. This is to allow room for the binding wires which are put on after the winding is completed. Sometimes the punchings are not slotted but are milled out and narrow bars of metal or wood inserted in

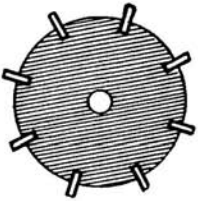


Figure 25.

the grooves as shown in Figure 25. These bars are for the purpose of keeping the wires from slipping. If of metal they must be insulated from the punchings for the same reason as was explained with the use of bolts.

In some cases the slots are made partially closed as shown. This makes it a little more difficult to insert the wires, but they are then held securely in place. Often these slots are made wedge shape and the tops closed by means of wood or fiber strips after the wires have been put in place. In some cases the slots containing the wires are entirely closed.

In slotted armatures, especially if the slots are deep, when the punchings are forced together that part of the punchings which projects beyond the ring R, Figure 20, is likely to bulge out. In order to prevent this a few pieces of extra heavy metal are obtained and used at the ends. One punching of insulating material is also generally used at each end.

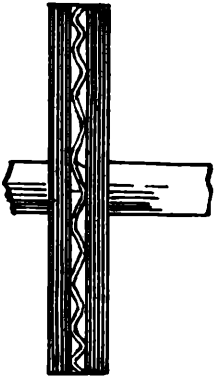


Figure 26.

For small armatures the punchings are generally left solid. With diameters of 18 inches or so openings are left. These openings lighten the armature and are also useful in ventilating it to reduce the heating. With very large armatures opportunities for radial ventilation must also be given. For this purpose some of the punchings are corrugated or otherwise arranged so that they allow air to pass from the center outward. When such pieces (see Figure 26) are used in connection with the openings shown in the punchings, the air drawn in at the sides escapes radially and thus helps to keep the armature cool. This is further illustrated in Figure 27, which shows one of the methods used by the Westinghouse Co.

The punchings are preferably made of metal ranging from 10 to 30 mils in thickness. The thinner the better so long as the metal can be easily handled. Punchings should be made as accurate as possible. Where it is necessary to turn down an armature to obtain perfect roundness the foucault current losses are greatly increased. This is due to the fact that the cutting tool of a lathe has a tendency to bend over the edges of the thin punchings and cause an electrical contact which allows

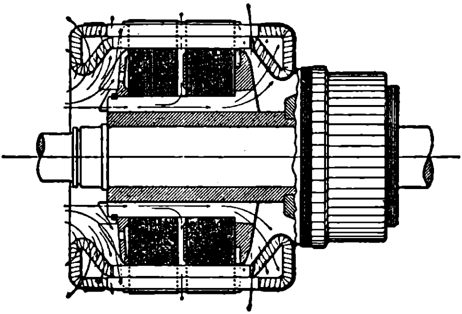


Figure 27.

current to flow. If it is necessary to smooth down an armature this work is best done with a sharp file or with an emery wheel. For this purpose the armature is centered in a lathe and the emery wheel mounted so as to revolve in the opposite direction to that of the armature and cut away the high portions of it.

In most of the modern armatures the windings are placed in slots and held in place by wedges. Where binding wires are needed to hold the coils in place it is customary to use the best steel or phosphor bronze wire. The necessary cross section of the total number of wires to be used for this purpose can be found by the following formula:

Wt. × D × r. p. m.^{2} × .000000000455; where Wt. equals the total weight of the conductors: D is the diameter of the armature in inches; and r. p. m. the number of revolutions per minute. As an example this gives us for Wt. 600, D 60 inches and r. p. m. 150, 0.368 square inches of metal which should be in the wire. To be exact the tensile strength of the wire in question should be taken into consideration but as that is hardly ever known to the workman the figures are based upon the strength of good material and therefore need not be used in the formula.

In the following table the number of turns per square inch of various B. & S. gauge wires have been figured out and may be used. In order to determine how many turns of wire of any of the sizes given are necessary we need but multiply the number of wires per square inch given by the result of the above formula.

Table showing number of wires per square inch.

B. & S. Gage	No. Wires
18	617
17	487
16	387
15	306
14	243
13	193
12	153

CHAPTER III.

ARMATURE WINDINGS—DIAGRAMS.

The subject of armature winding resolves itself into a question of the proper placing of the armature conductors upon the core, the correct number of conductors, and the exact method of connecting together the various conductors themselves and the conductors and the commutator segments.

The proper placing of the conductors, and the number of conductors which should be used, will be shown for the different cases in the examples following. In connecting together the various armature conductors it is necessary, in order to secure satisfactory results, that certain rules be followed.

It is evident that when two brushes are used there must be two paths in parallel through the armature from brush to brush, as shown in Figure 28. Figure 28 is a developed view of the armature conductors and pole pieces, and is that view which would be obtained were a person to take up a position corresponding to that occupied by the armature shaft and make a complete revolution, thus bringing into view consecutively all the armature conductors and the pole pieces. This method of showing the armature admits of a clearer understanding of the various conditions and will be used in the illustrations following. The solid lines represent the active conductors on the face of the armature and the dotted lines the inactive conductors on the inside of the armature. The small squares at the top represent the commutator segments and the cross sections the pole pieces. Arrows indicate the direction of flow of the induced current and the direction of motion of the conductors.

By observing the direction of current flow in the several conductors it will be seen that there is one commutator segment toward which the current in the two conductors connected to it flows. Likewise, another commutator segment will be found where current flows away from it. These are the proper brush locations and are designated in the diagram by the positive and negative signs. Figure 29 represents diagrammatically the two paths through this armature.

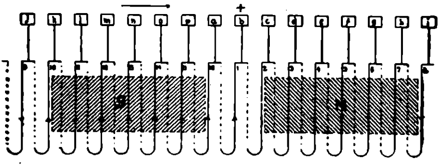


Figure 28.

Where four brushes are used there must be four paths in parallel from brush to brush, as shown in Figure 30, which is a development of the same armature winding as shown in Figure 28, but used with a four-pole field. Figure 31 represents diagrammatically the four paths through the armature.

It follows, therefore, that where two brushes are used there being two paths through the armature, it will be necessary, in order to obtain a symmetrical winding, that half the armature conductors be connected in series in each of these paths. With four brushes there will be four paths and one-fourth of the total number of armature conductors must be connected in series in each of these paths.

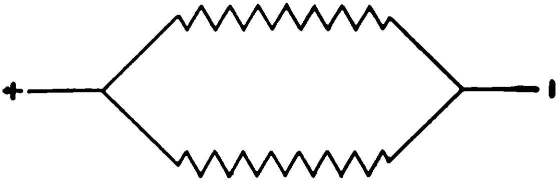


Figure 29.

It is also apparent that in each of these several paths only those conductors should be connected in series in which the induced current is additive. Furthermore, in order that equal potentials shall be produced, the conductors of each group must occupy similar positions relative to the pole pieces. This can be seen by an examination of the winding in Figure 44. As an illustration, assume that the conductors which lie directly under the center of the pole pieces are developing an E. M. F. of 2 volts, those nearer the edge of the pole piece 1 volt and those between the poles 0 volts. If the four paths between the two positive and negative brushes are now followed out it will be seen that each group of conductors is developing a difference of potential of four volts.

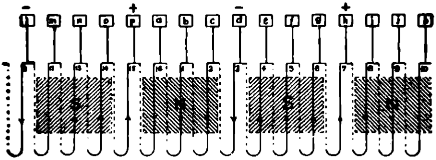


Figure 30.

As a general rule then, in connecting together the armature conductors, these points must be observed:

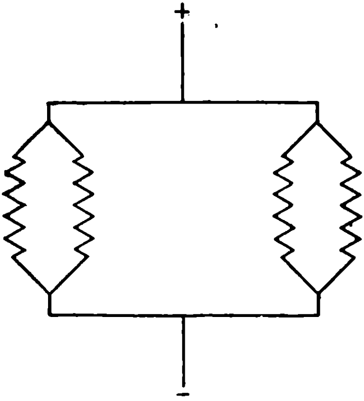


Figure 31.

Only those conductors must be connected together to form a group in which the E. M. F.'s are additive; there must be equal numbers of conductors in each group; the conductors of each group must occupy similar positions in relation to the pole pieces. The various factors which enter into the design of an armature sometimes make an exact compliance with these general rules inadvisable. The exceptions will be pointed out in the descriptions following.

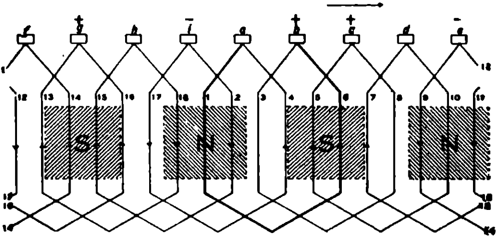


Figure 32.

Figures 32 and 33 represent the development of a drum wound armature, having 18 conductors and a four-pole field. The number of conductors and the method of connecting the conductors together at the rear of the armature (shown in the development by the connections at the lower part of the figures) are identical. The connections between the conductors, and between the conductors and the commutator segments are not the same in each case. As we have already seen, it is necessary in connecting together conductors to form a group that the E. M. F.'s be additive.

In Figure 32 if we start from commutator segment *i*, which in the position shown is the point where the current enters the armature, we will find by tracing out the circuit that current flows through conductors 17, 4, segment *a,* conductors 1 and 6 and out at segment *b*. The path through the armature between the two brushes is through conductors lying under adjacent north and south poles, and the winding at each turn around the armature laps back to a commutator segment adjacent to the one from which it started. This winding is known as the "lap" winding.

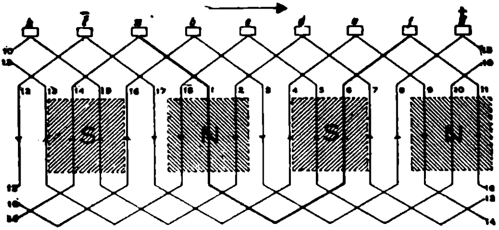


Figure 33.

It will be noticed that with a lap winding in a four-pole field there are four brushes. Likewise, in a six-pole field there would be six brushes; the lap winding requiring as many brushes as there are poles.

If we now trace out the circuits in Figure 33 it will be observed that, starting from the negative brush, the following path is followed: Segment *i,* conductors 17-4, segment *e,* conductors 9-14, segment *a,* when we arrive at the commutator segment adjacent to the one from which we started, but in this case we have passed through a conductor under each pole piece. This winding instead of lapping back as in the previous case progresses in a regular manner around the armature in a wave-like path and is therefore known as a "wave winding." By tracing out the balance of the circuit it will be found that there are two paths through the armature from brush to brush and only two brushes are required.

As has previously been stated in connecting together the conductors around the armature certain definite rules must be followed. A formula developed by Arnold, which is applicable to practically all cases of armature winding, gives us a convenient means of determining the proper connections to comply with these rules. This formula is given below.

$$y=\frac{2}{n}\left(\frac{z}{b}\pm a\right)$$

where y=the pitch,

z=total number of conductors,

b=number of conductors in one element of winding,

a=a constant,

n=number of poles.

To thoroughly understand the application of this formula some explanation of the various factors is necessary. The term z denotes the total number of conductors around the armature. In the diagrams shown in this chapter the armature conductors are represented as single lines or single conductors. For obvious reasons an armature wound with single conductors, especially if only a few conductors were used, would be impractical; but it is evident that if each coil consisted of a number of turns and the ends of the coil were connected as shown by the lines in the diagrams, the effect, so far as the armature connections are concerned, would be the same as if only one turn was used. In determining the value of z, therefore, we ignore the actual total number of conductors and consider each coil as a single turn around the armature. In Figure 40 $z=16$; in Figure 64 $z=18$.

An element of the winding is that portion of the winding between two commutator bars. The term b, therefore, represents the number of conductors between two commutator segments. In this case, as in the case of the total number of conductors, we consider each coil as one conductor. In Figure 40 $b=1$; in Figure 62 $b=2$.

The number of poles is denoted by the term n. In a bi-polar machine $n=2$; in a four-pole machine $n=4$, etc.

The value of a for multi-polar machines determines the number of branchings of the circuits through the armature. If $a=1$, there will be a single branching or two circuits in parallel as shown in Figure 29. If $a=2$, there will be two branchings or four circuits in parallel through the armature as shown in Figure 31.

The term y indicates the pitch or spacing, or the number of conductors passed over in connecting together two conductors. The meaning of the term y can be better understood by referring to Figure 34, which represents the end view of an armature with 12 conductors and 12 winding spaces. If the value of y is taken as 5 and we wish to know what conductor 1 should be connected to, we begin to count with conductor 2 and count five conductors, which would bring us to conductor 6, this being the 5th conductor or the 5th winding space from conductor 1. Conductor 3 would connect to conductor 8. If the value of y is 7, conductor 1 would connect to conductor 8; conductor 3 to conductor 10, etc.

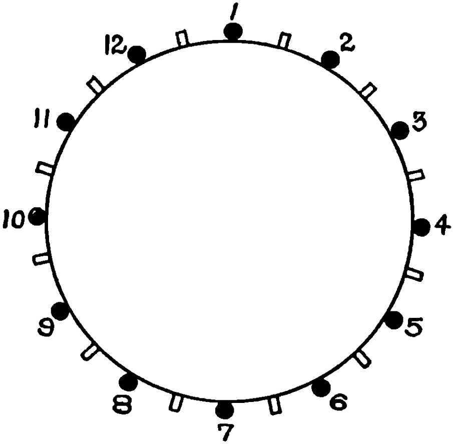


Figure 34.

To determine the number of conductors when we have a given pitch we transpose the terms of the formula which gives us

$$z=b\left(y\frac{n}{2}\pm a\right).$$

The application of this formula for the various classes of winding will be shown in the examples following:

Armature windings are divided into three general classes, as follows:

Ring wound armatures,
Drum wound armatures,
Disk wound armatures.

These windings are again subdivided into what are known as open coil windings, where the winding forms an open circuit; and closed coil windings, where the winding forms a closed circuit.

The ring winding and drum winding are in most general use and each system will be described in detail. As the disk winding has not had any extensive application in this country no further explanation of it will be given. On direct current machines the windings are generally of the closed coil type, although the open coil type of armature is employed on some constant current, arc lighting machines. This type of armature is open to the objection that sparking at the brushes is excessive and some special means must always be provided to reduce it.

RING WOUND ARMATURES.

The ring armature, or as it is commonly called, the gramme ring armature, comprises an iron core in the shape of a ring upon which the conductors which are to convey the current are wound. Figure 35 shows a simple form of ring winding. This figure also shows the magnetic circuit of this form of armature when used with a two-pole field. The coils are wound on separately, the wire being carried over the outside of the iron core, then back through the center opening and again around the outside of the core, this operation being repeated until all the wire for that individual section is wound on. The adjacent coil is then wound on in the same manner, the ends of each coil being brought out to the

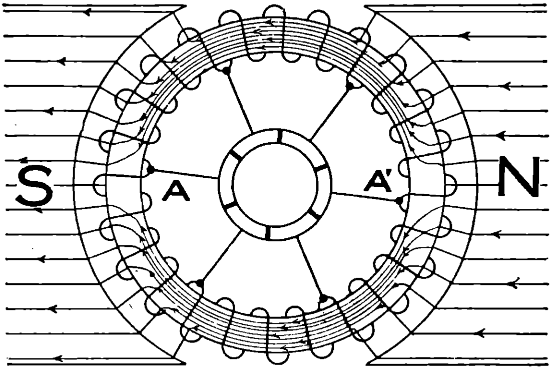


Figure 35.

side of the armature on which the commutator is to be placed. When the armature is completely wound the end of each coil is connected to the beginning of the coil next to it, the winding, therefore, forming a continuous spiral encircling the iron core. Taps are brought down from the point of connection of the coils and connect to the commutator.

There are various advantages and disadvantages to this class of winding which must be taken into consideration in determining whether it is a suitable form to use.

As only those conductors which cut lines of force are active in the production of current it is evident that the conductors which lie on the inner side of the iron ring serve no useful purpose so far as the generation of current is concerned. Numerous attempts have been made to utilize this part of the winding by making the pole pieces extend around the ring in such a manner that lines of force will pass to the inside of the ring; also by arranging an additional pole piece on the inside of the armature, but mechanical considerations make these devices impractical.

The inactive wire on the inside of the ring armature forms one of the greatest disadvantages of this class of winding, especially where the armature carries heavy currents. In arc lighting machines, where a comparatively small current is used, this loss is not of so great importance and is entirely outweighed by the several advantages as will appear after further consideration.

In selecting the type and form of armature for the design of a certain machine it is well to remember that with armatures of the ring type the inactive conductors on the inside of the ring become proportionally less as compared with a drum armature where the ring is great in diameter. The cross connections at the end of a drum armature also form an inactive part of the armature circuit and the loss from these conductors becomes proportionally large where the armature is of a great diameter. This may be better understood by reference to Figures 36, 37, 38 and 39, where exaggerated shapes are shown.

Figure 36.

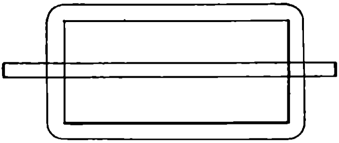
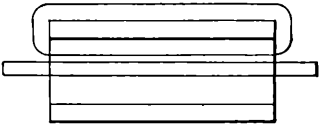


Figure 37.



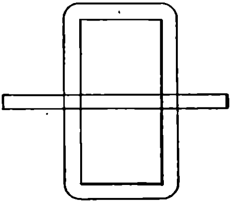


Figure 39.

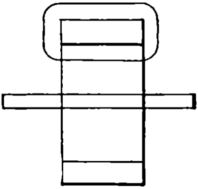


Figure 38.

With the ring armature each individual coil is generating at any instant an electromotive force which is proportional to the number of lines of force being cut by that coil. The difference of potential between conductors which lie side by side increases as we leave the point of commutation and becomes a maximum between those conductors which are in the strongest part of the field. It is evident that the total E. M. F. developed by the armature is spread out in a regular manner over each set of coils lying between a set of brushes and it is also plain that there can never be any very great difference of potential between adjacent conductors, nor between adjacent commutator segments. By increasing the number of coils the number of commutator segments is likewise increased and the difference of potential between adjacent commutator segments and adjacent coils is greatly reduced.

Another point of advantage in this type of winding lies in the absence of crosses between wires of opposite polarity, both in the coils themselves and in the taps extending to the commutator. This will be more apparent when we come to the consideration of drum windings.

Other advantages pertaining to this class of winding are as follows:

As it is possible to increase the diameter of the armature without greatly increasing its weight a much higher velocity can be obtained in the moving conductor with a corresponding increase in the E. M. F. produced.

A defective coil can be easily detected and easily replaced without disturbing the balance of the winding.

In case of emergency a defective coil can sometimes be cut out and the machine still operated.

Better ventilation due to the open style of construction.

Its disadvantages in addition to those already mentioned are:

The resistance of the magnetic circuit is increased owing to the shape of the armature. See Figure 35.

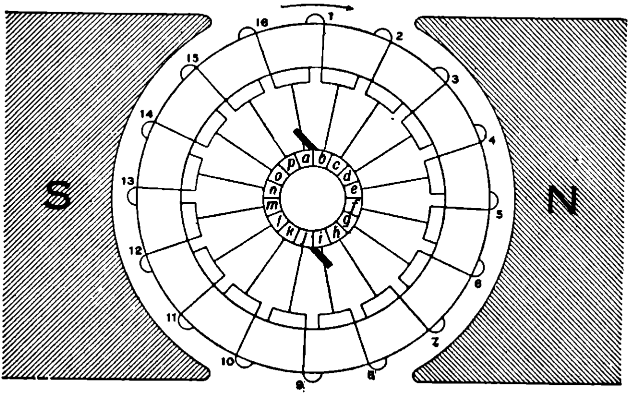
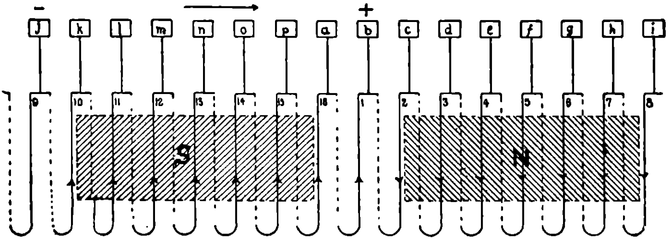


Figure 40.

A ring armature requires more work to wind as each coil has to be wound on by hand and is, therefore, more expensive.

While all ring armatures are wound in practically the same manner, the winding consisting of a number of coils each of which is wound on separately, the connections between the coils vary in the different types of windings.

Figure 40 shows the simplest form of ring winding as used with a bi-polar field. While only 16 conductors are shown it is evident that each coil, instead of having but one turn of wire, could consist of a number of turns, or the number of coils themselves could be greatly increased. To simplify the drawing, and to make the tracing out of the circuits easier, the neutral point or point of commutation in this figure, and in the figures following, has been assumed to lie directly between the pole pieces. It will, as has already been explained, be shifted in the direction of rotation in the case of a dynamo, and in the reverse direction in the case of a motor. Figure 41 shows a development of the winding of Figure 40.



igure 41.

Figure 42 shows a ring armature with a four pole field. The armature connections remain as before, but there are now four brush positions instead of two. The resistance of the armature is only one-fourth of what it is with a two pole field and the carrying capacity is doubled. As there are four paths through the armature, and each of these paths must consist of an equal number of conductors, the total number of conductors (or coils) should be a multiple of the number of pole pieces. For instance: with a four pole field there could be 16, 20, 24, etc., conductors.

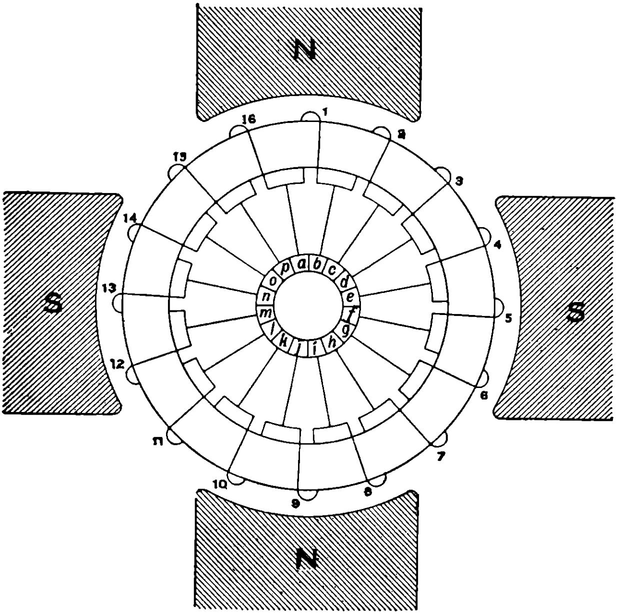


Figure 42.

With an armature connected according to the plan shown in Figure 42 it is necessary, in order that equal

E. M. F.'s be generated in each of the four sections of the armature winding, that all four poles be of equal strength. In machines of irregular design the magnetic circuits through the pole pieces may be of unequal proportions, this resulting in an unequal distribution of the lines of force, with a corresponding inequality in the E. M. F.'s developed in each series of coils on the armature.

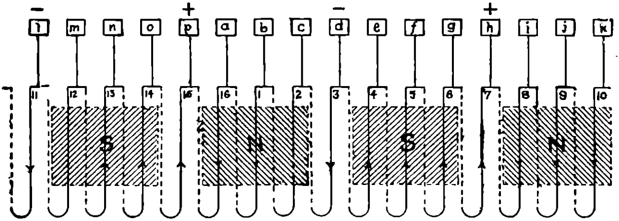


Figure 43.

To overcome this objectionable feature the armature may be connected as shown in Figure 44. The coils which are connected in series now lie under adjacent pole pieces instead of under only one pole piece with the result that the E. M. F. developed by each series of coils is more uniform even if the poles are of different strengths.

Four brushes are used, but the number of commutator segments is now reduced to eight, or one half the number used with the previous winding. The difference of potential between adjacent commutator segments is greatly increased and likewise the difference of potential between adjacent coils. There are also numerous crosses between the conductors connecting the various coils. This is, of course, objectionable as a better insulation is required.

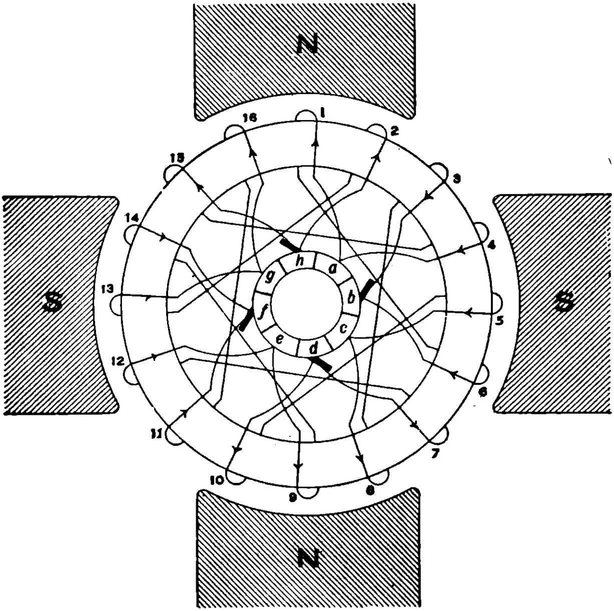


Figure 44.

It will be noticed that the end of coil 1 is connected to coil 6, coil 3 to coil 8, etc., each coil being connected to the fifth coil from it. It might at first glance be supposed that coil 1 should be connected to coil 5, these coils occupying similar positions relative to the pole pieces, but a little consideration will show that this connection would be wrong. If coil 1 and coil 5 were connected together the path through the armature would be as follows: Commutator segment *a* to coil 1, coil 1 to coil 5 to segment *b*, coil 3 coil 7 segment *c*. To make the connections uniform segment *c* would have to be connected to coil 5, but this coil is already connected to coil 1.

Tracing out the armature circuits between the positive and negative brushes will show that in each series the coils occupy similar positions relative to the pole pieces and equal E. M. F.'s are being developed.

In applying the formula previously stated to the winding scheme now being described we consider only those conductors which lie under one pair of poles and then give n (the number of poles) a value of 2. In Figure 14, $z = 8$ and $b = 2$, therefore $y = \frac{2}{2}\left(\frac{8}{2} \pm 1\right) = 3$ or 5. The formula written in simpler form for this case gives us $y = \frac{z}{n} \pm 1$, in which case z is taken as the total number of conductors. $y = \frac{16}{4} \pm 1 = 3$ or 5. As shown in the figure, the end of any coil is connected to the beginning of another coil 5 conductors, or 5 winding spaces, from it; as, conductor 1 to conductor 6, etc.

A method of connecting the armature similar to the one just described consists in connecting four coils in series, one coil under each pole piece, it being necessary, of course, to so connect the coils that the current induced in each coil will be added to that of the remaining coils. Connecting the armature in this manner still further adds to the uniformity of the E. M. F.'s induced in each series of coils as any irregularity in the strengths of the pole pieces affects all the branches alike. This connection is objectionable as the number of commutator segments would be reduced to one-fourth the number of coils and a corresponding increase in the difference of potential between the commutator segments would result.

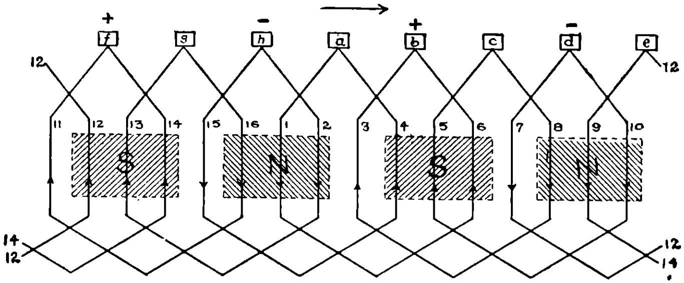


Figure 45.

Figure 46 illustrates a connection which is often used, especially where the machine is to deliver a heavy current at a low voltage. As will be seen by an examination of the diagram, the winding consists of two sets of windings similar to the one shown in Figure 40 placed side by side. The voltage developed by an armature connected in this manner would be the same as that developed by the single winding referred to above, all other conditions being the same, but the carrying capacity of the armature where the same size wire was used would be doubled. The brushes must be of such size as to make contact with the two adjacent segments at the same time; as a matter of fact the brushes generally cover from two and a half to three commutator segments with the intervening insulation. An important feature of this arrangement lies in the reduction of the sparking at the commutator owing to the fact that only half the current of the armature is commutated at one time, and

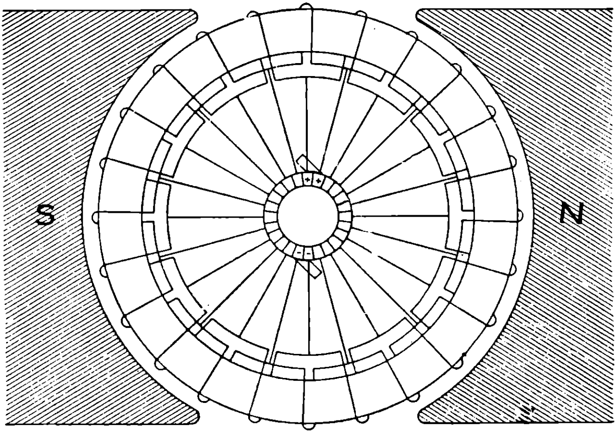


Figure 46.

also due to the considerable length of carbon brush between the short circuited sections. As the commutator segments connected to one set of coils are separated from each other by the segments of the other set, the possibility of short circuits across the commutator segments is greatly reduced. This style of winding is known as the "duplex," and a winding connected with three sets of coils in parallel is known as a "triplex" winding. This principle of winding can be applied to any of the schemes

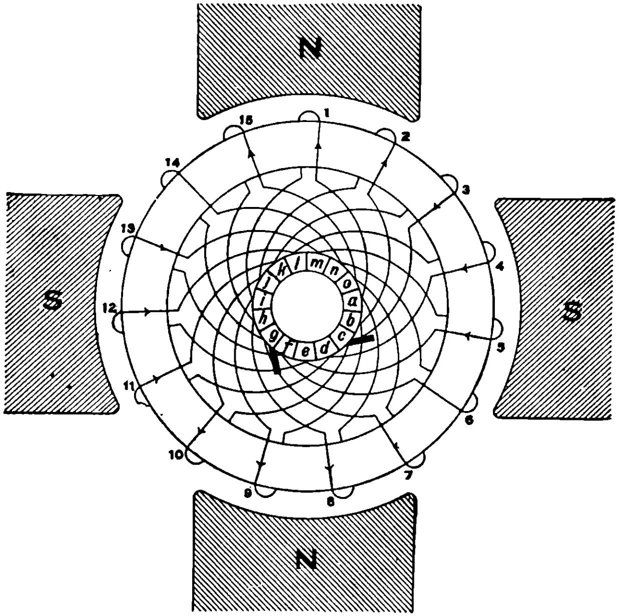


Figure 47.

shown and may be further extended to include any number of paths in parallel.

Figure 47 shows a plan of winding for a four pole field where, instead of four brushes, only two are used. In Figure 44 four brushes are used and the current follows four paths through the armature. In the present case there are only two paths through the armature from the positive to the negative brush, each circuit consisting of practically one-half the coils in the armature. This is known as a "wave" winding and will be described more in detail under the head of "Drum Windings." The connections may be so arranged that the coils in adjacent fields are connected together instead of coils in opposite fields. This latter connection is known as the "long" connection due to the fact that the conductors between the coils connected together are long, while the connection shown in Figure 44 is called the "short" connection.

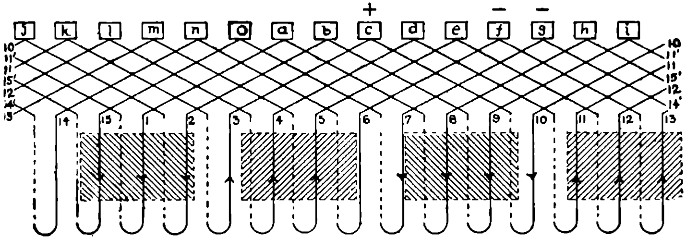


Figure 48.

It will be noticed that there are as many commutator segments as coils. For a winding of the kind shown (long connection) the number of coils must be odd if an even number of pairs of poles are employed. For instance, if four poles are used, there must be an odd number of coils. See Figure 47. If six poles are used, the number of coils can be even or odd. The expression for determining the correct spacing is as follows: $n=4$, $z=15$, $b=1$, $a=1$. $y=\frac{2}{4}\left(\frac{15}{1}\pm 1\right)=7$ or 8. As for example, in Figure 47 the beginning of coil 1 is connected to the end of coil 8; coil 2 to coil 9, etc., the spacing being 7.

OPEN CIRCUIT, RING WOUND ARMATURES.

Open circuit, ring wound armatures for the generation of direct current are used only with series arc light generators. Figure 49 shows diagrammatically the circuits of a Brush armature with 8 coils. The commutator has, for clearness, been represented as segments of concentric circles. As actually constructed the commutator surrounds the armature shaft with brushes bearing on it in the usual manner.

The coils are wound on the core in the customary manner; i. e., all coils wound spirally in the same direction. The diametrically opposite coils are connected in series, the remaining ends being connected to the two commutator segments lying in the same circle, each segment extending around ⅜ of the circle. Each coil is, therefore, on open circuit twice during a revolution, and the commutator is so arranged that at the time of open circuit the coils are in the neutral position.

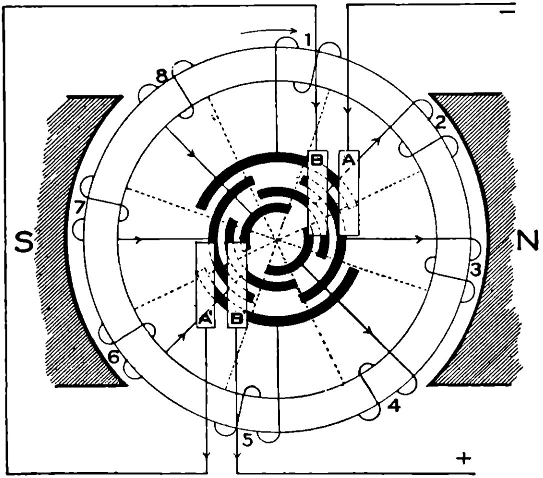


Figure 49.

For every two pairs of coils lying at right angles to each other there are four commutator segments and two brushes bearing on these commutator segments. The armature may, therefore, be wound with any number of coils so long as the total number is a multiple of four, and for every four coils there must be one set of brushes. This may be seen by referring to Figure 49 where there are eight coils and two sets of brushes.

Following out the circuit through the armature for the position shown in the figure it will be found that the current takes the following path: Brush A, coil 3, coil 7, brush A′, brush B, coils 2 and 4 in parallel, coils 6 and 8 in parallel, brush B′. It will be noticed that coils 1 and 5 are completely cut out of circuit when the armature is in the position shown, or when these coils are at the neutral point. It will also be noted that coils 3-7 which are generating their maximum E. M. F.'s are connected in series with coils 2-4 and coils 6-8, these latter coils being connected in parallel and generating only a portion of their maximum voltage.

As the armature revolves from the position shown coils 2-6 will come into the position of maximum voltage and these coils will then be connected in series with coils 1-3 and 5-7 which are in parallel. Coils 8-4 will be cut out. This action is continued as the armature revolves.

When the coils approach the position of open circuit a small current still flows through them as they are then in a live part of the field. As the contact between the brush and commutator segment is broken a considerable spark results. This is one of the peculiarities of an open coil machine and is evidenced by the severe flashing when the machine is operating.

DRUM WOUND ARMATURES.

The drum wound armature varies primarily from the ring wound armature in the shape of the core. While with the latter the core is in the shape of a ring or hollow cylinder, the conductors being wound spirally around the ring; with a drum wound armature the core is in the shape of a solid cylinder, or drum, and the conductors are wound around the outside surface in a direction parallel to the shaft. It must not be understood that the shape of the core alone determines the class of winding, for in some machines a drum winding is placed on a ring core. The distinguishing characteristic of the ring winding lies in the fact that the active conductors, which pass over the face of the armature from the front to the back, have their return conductors pass through the opening in the center of the ring from the back to the front, this part of the conductor being inactive in the production of current. In a drum winding the conductors in returning from the back to the front of the armature also pass over the face of the armature where they can cut lines of force and are also active in the production of current.

It will thus be seen that in the ring armature considerable of the wire is not only inactive in the production of current but at the same time is the cause of a loss of energy due to its resistance, with a resulting heating of the armature. This objectionable feature is to a great extent overcome in the drum wound armature. Less wire has to be used on a drum wound armature, other conditions being equal, than on a ring wound armature of the same capacity and the armature has a lower resistance.

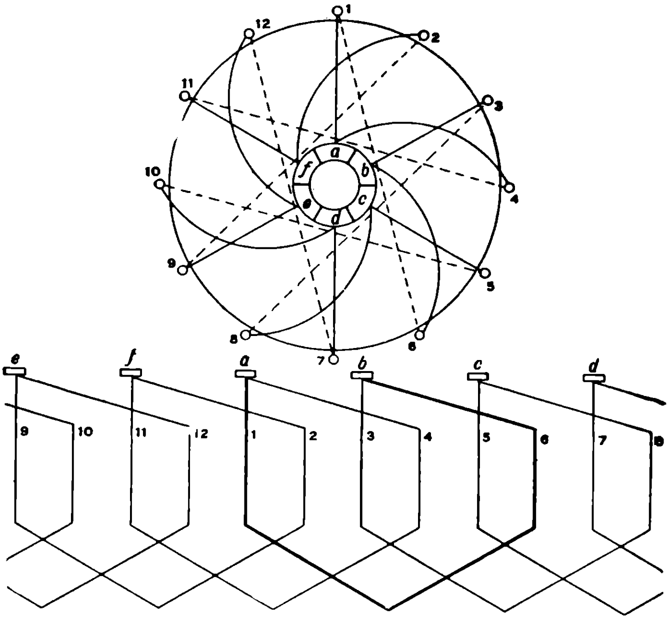


Figure 50.

At first glance the winding of a drum armature appears quite a difficult matter, but with a little study it will be found that it is not very much unlike that of the ring armature. A simple case of drum winding is shown in Figure 50. There are 12 conductors on the armature face and 6 commutator segments. Suppose we take a wire and connect it to segment *a* of the commutator. Now start to wind around the armature passing along 1 to the rear and returning by way of 6 to the front where we loop back to commutator segment *b*. Now make another turn around the armature by way of 3 and 8 returning to segment *c* of the commutator. Repeat this procedure, gradually turning the armature to the left. When the last turn, 11-4, has been made we come back to commutator bar *a*, the one from which we started. It will be seen that this operation consists simply in winding a wire spirally around the armature, bringing down loops to the commutator segments, and ending at the point from which we started.

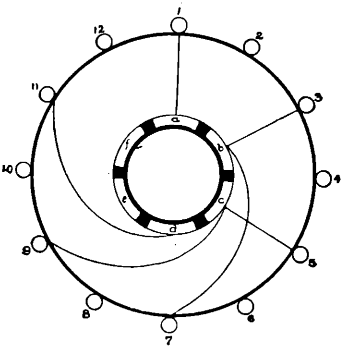


Figure 51.

The first question which presents itself to the student is: Why does not the wire which passes over space 1 return in the diametrically opposite space or 7? Consider for a moment the armature shown in Figure 51 which is identical with the last except for the winding. Suppose we start our wire at segment *a* of the commutator, pass to the rear of the armature along space 1 and return to the front of the armature along the diametrically opposite space, 7. Now loop back to segment *b* of the commutator and from there make another turn around the armature by way of 3-9 and back to segment *c*. From segment *c* make another loop around the armature by way of 5-11 and return to segment *d*. It will now be seen that we have made a complete revolution of the armature but have made connection to only half the commutator segments. In order to keep up the winding in a regular manner the wire from segment *d* should pass to the rear of the armature along space 7, but this space we find already occupied by the return of 1. If we were to continue with our winding from this point we would have to carry the wire from segment *d* to position 6 or 8, but this would result in an unbalanced winding.

It is plain that in order to keep the winding symmetrical the conductors in passing from the front to the rear of the armature must occupy the positions 1-3-5-7-9-11 and the even numbered positions will then serve as returns for these wires.

It will be noticed that in the example shown there are 6 coils, comprising 12 conductors, and 6 commutator segments. If the armature was so designed that we had an uneven number of coils, 7 coils with 14 conductors for instance, and 7 commutator segments, the rear connections could be made directly across a diameter as shown in Figure 52. This gives a perfectly symmetrical winding.

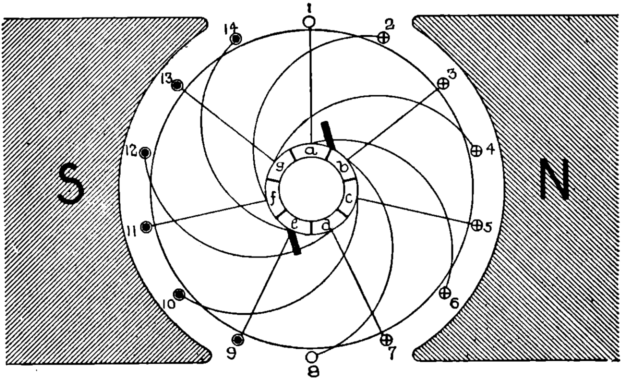


Figure 52.

For the sake of clearness the rear connections are not shown in the drawing but are made across a diameter; as, 1-8, 3-10, etc. The winding table for this armature is:

a- 1- 8-b
b- 3-10-c
c- 5-12-d
d- 7-14-e
e- 9- 2-f
f-11- 4-g
g-13- 6-a

An examination of the development (Figure 53) will show that there are two brush positions, the positive brush on segment *e* and the negative brush lapping over segments *a* and *b*. This is also shown in Figure 52. There being an odd number of commutator segments and the brushes being set in diametrically opposite positions, it is evident that only one coil can be short-circuited at a time and this coil can occupy the exact neutral position. See Figure 52, coil 1-8.

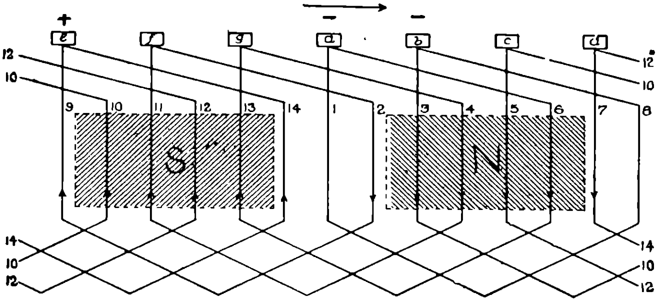


Figure 53.

The two paths through the armature from brush to brush are:

$$-\left\{\begin{array}{l}\text{b-3-10-c-5-12-d-7-14-e}\\ \text{a-6-13-g-4-11-f-2-9-e}\end{array}\right\}+$$

Figure 54 shows the connections of a drum-wound armature having 8 coils comprising 16 conductors, and 8 commutator segments. While in the example shown each coil consists of only a single loop with two conductors, a coil may consist of a number of turns of wire, in which case the drawing indicates merely the connections for the beginning and end of each coil.

As has been previously explained the conductor which passes from the front to the rear of the armature along space 1 cannot be brought back to the front of the armature along the diametrically opposite space but must return along one of the spaces to the right or left of 9. The expression for determining the proper spacing for the return conductor is: $y = \frac{2}{n}\left(\frac{z}{b} \pm 1\right)$. In Figure 54, $n=2$, $z=16$, $b=2$, therefore $y = \frac{2}{2}\left(\frac{16}{2} \pm 1\right)$ $=7$ or 9. The spacing 7 has been used, each conductor

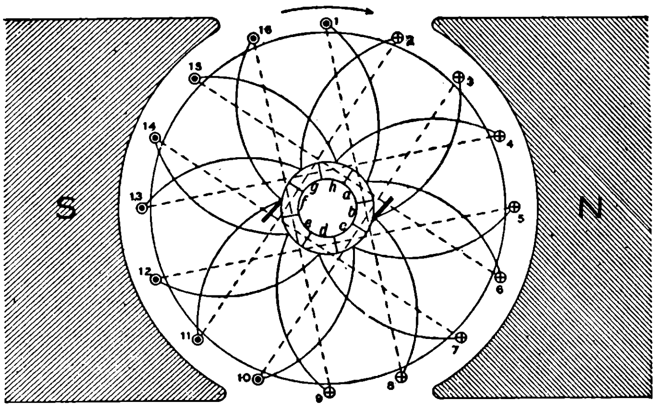


Figure 54.

being connected at the rear of the armature to one 7 spaces, or conductors, in advance of it; as, 1 to 8, 3 to 10, etc.

In winding the armature according to the plan shown, where each coil consists of a number of turns of wire, we would start with the wire connected to commutator segment *a* and wind along space 1 to the back of the armature, thence across the back to space 8, returning to the front of the armature along space 8 and across the front to space 1, continuing in this manner until all the wire of this coil is wound on. The end of the wire would now be brought to segment *b* of the commutator. The second coil is now wound on, starting from segment *b* and winding to the back of the armature along space 3, across the back to space 10, to the front along space 10 and across the front to space 3, con-

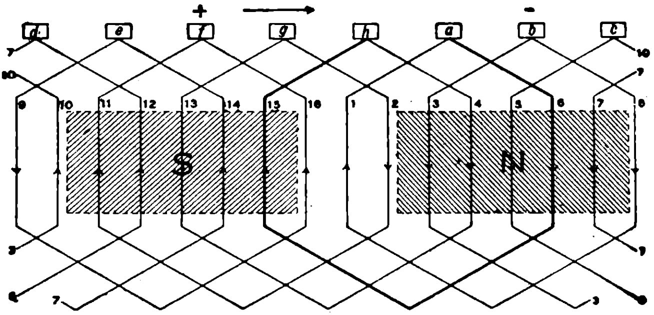


Figure 55.

tinuing the winding until this coil is also wound on. The end of this coil is now brought to commutator segment *c*. The remaining coils are now wound on in the spaces indicated.

In the practical operation of winding an armature the commutator is generally left off during the process of winding, the beginning and end of each coil being brought out and connected to the commutator after the armature is completely wound. A winding table which shows the several steps just described and which is very convenient both for winding and connecting is given below.

a-1- 8-b
b-3-10-c
c-5-12-d
d-7-14-e
e- 9-16-f
f-11- 2-g
g-13- 4-h
h-15-6-a

This table shows both the position of each coil and the commutator connections; for instance, segment *b* is connected to the end of coil 1-8 and to the beginning of coil 3-10.

The development of the armature winding, Figure 55, shows in a plainer manner the various connections made, also the direction of flow of the induced current in the various conductors. Following out the direction of flow of current it will be seen that at commutator segment *f* the current in both conductors flows toward the segment, while in segment *b* current flows away from the segment. These two positions are the proper points for the brush contacts.

With the armature connected as shown the brushes lie in an almost direct line with the pole pieces and the connections on the front of the armature are symmetrical. It is quite evident that we could, without changing the order of the winding, turn the commutator through an angle of 90°, thus bringing the brushes in a line with the space between the pole pieces. The front connections would not then be symmetrical, one connection to each coil being shortened and the other being lengthened. The mechanical design of some machines is such that locating the brushes in a line with the pole pieces brings them in an inaccessible position and the commutator is therefore shifted as described.

The two circuits through the armature from brush to brush for the position shown are:

$$-\left\{\begin{array}{l}\text{b-3-10-c-5-12-d-7-14-e-9-16-f}\\ \text{b-8- 1-a-6-15-h-4-13-g-2-11-f}\end{array}\right\}+$$

As the armature revolves in the direction shown by the arrows the positive brush will short circuit commutator segments *e* and *f*, and the negative brush segments *a* and *b*. The two coils e-9-16-f and b-8-1-a will therefore be short circuited and the full difference of potential of the machine will exist between them. These coils being adjacent, with a smooth face armature where the coil consists of a number of turns of wire, wires of a very great difference of potential will lie side by side and the question of insulation between them becomes of considerable importance.

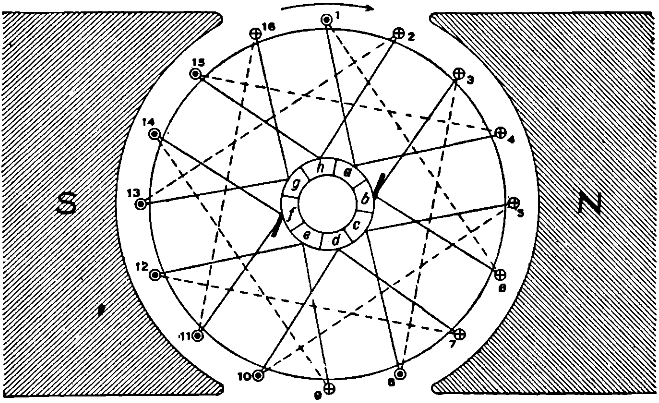


Figure 56.

Following out the paths on the development of the winding will also show that there are numerous crosses between wires of greatly different potentials. Compare with the ring armature winding shown in Figure 40.

To obviate some of the objectionable features of the winding just described the method of winding shown in Figure 56 is used. The value of y, or the pitch, is in

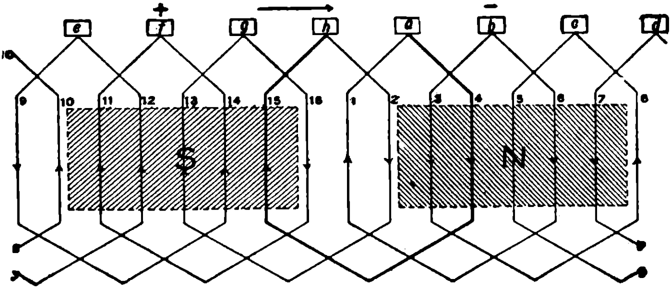


Figure 57.

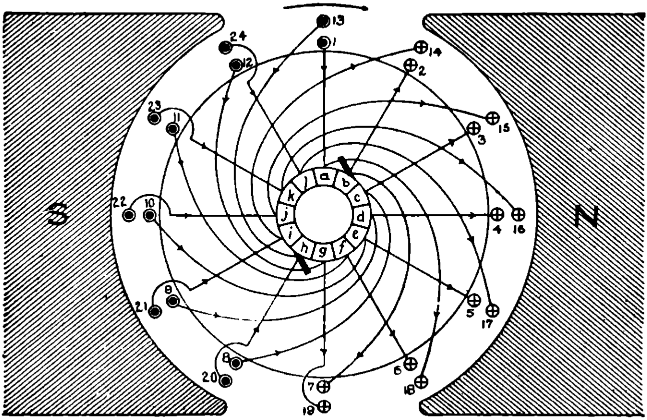


Figure 58.

this case 5, each conductor being connected at the rear of the armature to a conductor 5 spaces ahead of it The coils short circuited by the brushes are now separated and there are fewer crosses between conductors at the end of the armature. Tracing out the circuits it will be seen that the current induced in some of the conductors is in opposition to that induced in the remaining conductors of the group. This has the effect of decreasing the demagnetizing effect of the armature turns. See Figure 56.

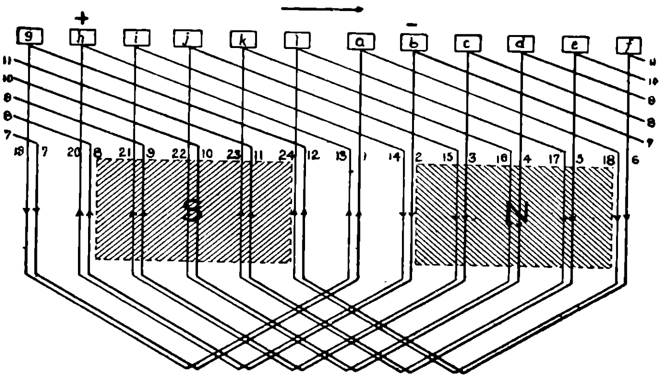


Figure 59.

The armatures which have so far been considered have had but one layer of wire. Figure 58 shows an armature with 24 conductors and 12 commutator segments with the wire placed on in two layers. The development of this winding is also shown in Figure 59. The winding table is given below:

a-1- 7-b
b-2- 8-c
c-3- 9-d
d-4-10-e
e-5-11-f
f-6-12-g
g-19-13-h
h-20-14-i
i-21-15-j
j-22-16-k
k-23-17-l
l-24-18-a

One of the first points that will be noticed is that each conductor in returning from the back of the armature to the front passes through the diametrically opposite space; coil 1-7, for instance. The rear connections are not shown as they would complicate the drawing. If we start to wind this armature from commutator segment *a,* winding coil 1-7, returning to segment *b* and continuing our winding from segment *b,* coil 2-8, segment *c,* coil 3-9, segment *d,* coil 4-10, segment *e,* coil 5-11, segment *f* to coil 6-12 it will be seen that we have made a complete revolution of the armature and have only made connection to half the commutator segments. We can complete the winding by continuing in the outer layers.

It is evident that the outer layer of coils will have a greater resistance than the inside layer, due to their increased length, and that they will also travel at a greater speed than the inside layer. The two paths through the armature from the negative to the positive brush vary between the coils in the outer layer and those in the inner layer and in one position of the armature one of the paths from brush to brush is through the coils of the inner layer exclusively, and the other path through the coils of the outer layer. This results in a constant variation between the E. M. F.'s induced in the two halves of the armature.

The two paths through the armature from brush to brush for the position shown are:

$$-\left\{\begin{array}{l}\text{b-2-8-c-3-9-d-4-10-e-5-11-f-6-12-g-19-13-h}\\ \text{b-7-1-a-18-24-l-17-23-k-16-22-j-15-21-i-14-20-h}\end{array}\right\}+$$

As the amature moves forward from the position shown coil 1-7 is short circuited by the negative brush and coil 13-19 by the positive brush. It will thus be seen that a considerable difference of potential exists between the inner and outer layers of wire, and they will have to be well insulated from each other. It will also be seen that no great difference of potential exists between adjacent conductors. The two short circuited coils lying one above the other are both in the neutral part of the field at the time of commutation. This is somewhat of an advantage over the previous method shown where the short circuited coils are separated and are therefore not commutated at the exact neutral point.

If the number of conductors on the armature is such that one-fourth of the total number is odd, a winding will be obtained which will give in each of the paths between the brushes an equal number of conductors lying in the outer and inner layers, and the inequalities between the E. M. F.'s generated in the two halves of the armature will be avoided. Figure 60 shows the connections for an armature with 20 conductors; ¼ of 20=5, an odd number. Tracing out the paths from the positive to the negative brush will show that in each of the paths there is an equal number of conductors in the two layers.

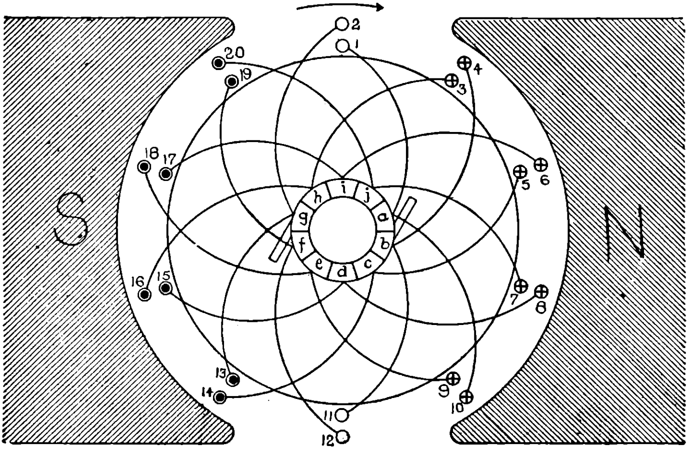


Figure 60.

Figure 62 shows a method of winding with two layers of wire where, instead of returning to the front of the

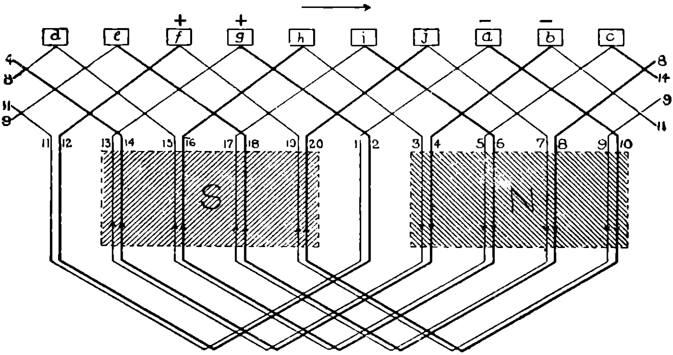


Figure 61.

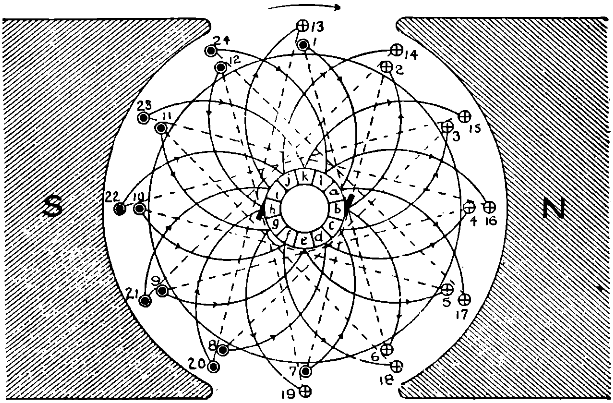


Figure 62.

armature over the diametrically opposite space, the return is made one space to the right. This has the effect of shortening the cross connections on the front and the rear of the armature with a result that less wire is used and the end connections are not as bulky as where the wire has to be carried around the armature shaft to get to the diametrically opposite space. The table for this winding is as follows:

a -1- 6-b
b- 2- 7-c
c- 3- 8-d
d- 4- 9-e
e- 5-10-f
f-18-11-g
g-19-12-h
h-20-13-i
i-21-14-j
j-22-15-k
k-23-16-l
l-24-17-a

Starting from segment *a* coil 1-6 is wound on, the end being connected to segment *b*. Coils 2-7, 3-8, 4-9, 5-10, are then wound on in the order given. In winding the next coil we find that space 6 is already occupied so that this coil will have to occupy the outer layer or 18, being brought back to the front of the armature along space 11. The remaining coils will now each occupy one space in the outer layer and one space in the inner layer until we arrive at coil 20-13 where the entire coil is now placed in the outer layer. It will be seen that the paths through the armature from brush to brush are somewhat equalized as compared with the first method given.

It will be observed that in the diagram Figure 62 the commutator is so placed that each segment lies between the coils to which it is connected and a symmetrical arrangement of the end connections is obtained. This is of great importance where heavy conductors are used. The armature shown in Figure 58 could be so arranged by shifting the commutator to the right.

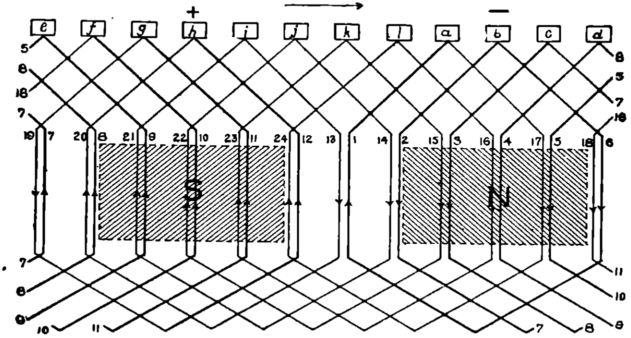


Figure 63.

The development, Figure 63, shows the brush positions and the direction of the current in each conductor.

With the armature in the position shown the two paths from the negative to the positive brush are:

$$-\left\{\begin{array}{l}\text{b-6-1-a-17-24-l-16-23-k-15-22-j-14-21-i-13-20-h} \\ \text{b-2-7-c-3-8-d-4-9-e-5-10-f-18-11-g-19-12-h}\end{array}\right\}+$$

The current in conductor 13 (in the upper row of figures) and 7 (in the lower row) is in opposition to that in the other conductors lying in the same space with them. The demagnetizing effect of the armature currents is thereby decreased.

As the armature moves to the right the positive brush will short circuit coil 12-19 and the negative brush coil 1-6. As will be seen by examining the figure these coils are in the active part of the field.

In the previous examples of drum winding we have considered only the methods of winding with bi-polar fields. As has been explained elsewhere there are many conditions where the use of a bi-polar field is not advisable and numerous advantages are gained by using a multi-polar field, or a field consisting of more than one pair of poles.

The same general principles apply to multi-polar windings as apply to bi-polar windings and while there are numerous schemes of winding, the application of only those methods in common use will be described.

Figure 64 shows an armature winding with its development, Figure 65, consisting of 18 conductors and a four-pole field. Following out the circuit from one

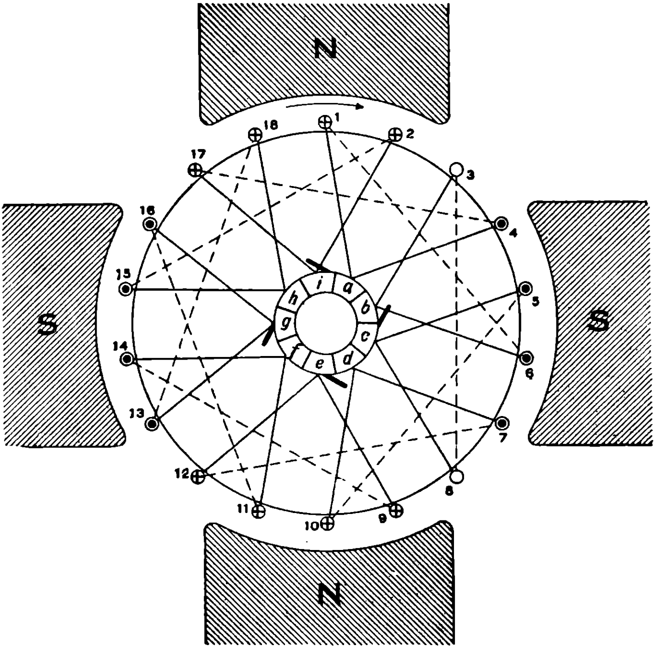


Figure 64.

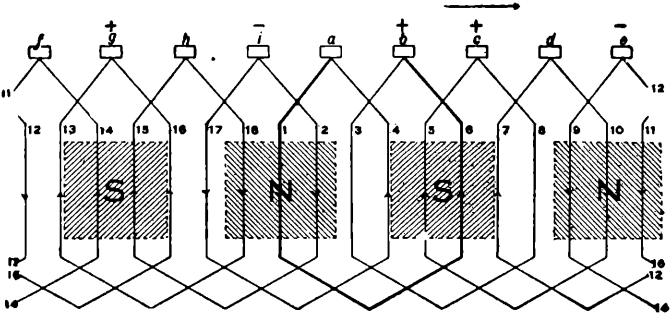


Figure 65.

commutator segment to the next on the developed winding it will be seen that, after making a turn of the armature, the winding laps back to the commutator segment next to the one from which it started and it is therefore called a "lap" winding. Tracing out the winding from commutator segment *a* we find it follows the path a-1-6-b, b-3-8-c, c-5-10-d, etc., until it arrives at the coil i-17-4-a where it returns to the starting point. A complete revolution of the armature has been made and every conductor has been passed through, and each one only once, forming what is termed a single reentrant winding.

Observing the end connections of coil a-1-6-b, for instance, it will be seen that the value of y for the rear connection is 5; each conductor at the rear of the armature being connected to a conductor 5 spaces beyond. The value of y for the front connection is —3; each conductor being connected to a conductor 3 spaces, or conductors, back from it. The average spacing is therefore 4 and the difference between the front and rear spacing is 2.

In connecting up the armature for a bi-polar field, in order that the induced currents would flow in the same direction in all the conductors connected in series we found it necessary to connect together at the rear of the armature the conductors lying under a north pole with those lying almost directly opposite it under a south pole. So, in the case of a four-pole field, each conductor at the rear of the armature is connected in series with a conductor which lies in a field of opposite sign which, in this case, is not across a diameter but one-fourth the distance around the armature. The value of y, the pitch, should therefore be nearly equal to the total number of conductors divided by the number of poles, or $\frac{z}{n}$, where z=the number of conductors and $n=$ the number of poles. As explained under the section on bi-polar armatures this spacing may be either greater or less than the value just given. If the spacing is greater than $\frac{z}{n}$ the cross connections will be longer with a resulting increase in the armature resistance. With the spacing less than $\frac{z}{n}$ the cross connections will be correspondingly shortened and the armature resistance lessened but the current will flow in opposite directions in the conductors which lie between the pole pieces, in the same manner as described for the short cord winding as used with a bi-polar field (Figure 56), and the demagnetizing effect of the armature will be reduced.

In Figure 64 it will be noticed that there are an even number of conductors, and that the pitch at the rear is 5 and at the front —3. In all lap windings with multi-polar fields there must be an even number of conductors and the pitch at the front and rear must be odd and must differ by 2.

A simple plan by means of which the student may investigate these several conditions consists in drawing roughly a circle, subdividing it with as many intersections as there are conductors on the armature and then drawing a series of connecting lines through the various points. These lines will then represent the armature conductors and their connections, the lines on the outside of the circle representing the rear connections and the lines on the inside of the circle the front connections.

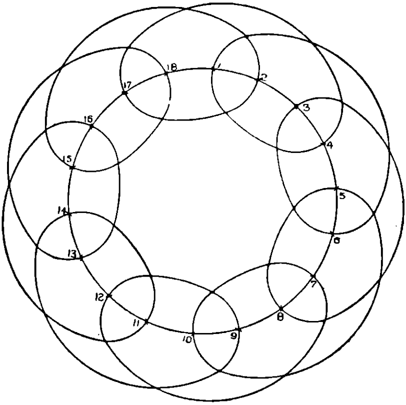


Figure 66.

Figure 66 shows this scheme drawn out for the armature shown in Figure 64. That the armature must have an even number of conductors can be seen by figures similar to that shown in Figure 67. Here 17 conductors are shown with a rear spacing of 5 and a front spacing of —3. The line from 13 should connect to a conductor 5 spaces beyond, or conductor 1, but this conductor is already connected to conductor 6.

With a bi-polar field and a one-layer winding it will be remembered that adjacent commutator segments were connected to every other conductor, the even-numbered conductors being taken as returns for the odd-numbered conductors. Similarly in a multi-polar armature our spacing must be such that only every other conductor is connected to a commutator segment. The front and rear spacings must therefore differ by 2.

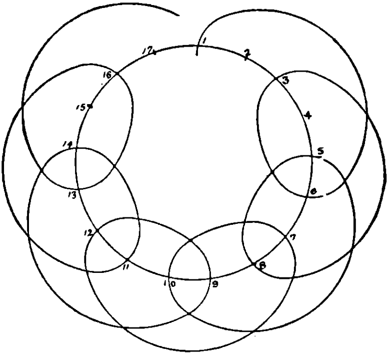


Figure 67.

That the front and back spacings must be odd can be easily determined with the scheme previously described. Figure 68 shows an armature with 18 conductors and a spacing at the rear of 6 and at the front 4. We see here that the loops close on themselves and would form a short-circuited winding.

With a lap-wound armature there are as many paths through the armature, and as many brushes, as there are poles. This can be seen from the development (Figure 65), the paths through the armature being as follows:

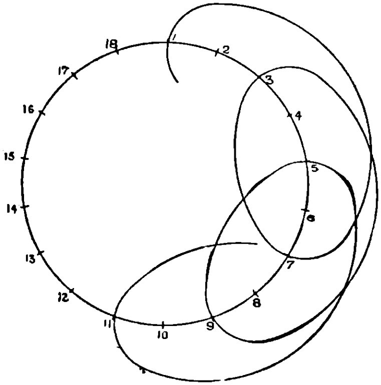


Figure 68.

— i- 2-15-h-18-13-g +
— i-17-4-a- 1- 6-b +
— e-12- 7-d-10- 5-c +
— e- 9-14-f-11-16-g +

These paths are unequal in length, as will be noticed from the drawing when the brush which bears on the commutator segments *b* and *c* has moved from this position. In order that all paths be of equal length the number of coils must be a multiple of the number of pairs of poles. For example, 16 conductors (8 coils) with a four-pole field (2 pairs of poles) would give uniform paths, each containing an equal number of coils. The objection to this arrangement lies in the fact that four coils would be short-circuited at the same time. An examination of Figure 65, where the number of coils is not a multiple of the number of pairs of poles, will show that four coils are not short-circuited at the same time. Where the number of coils is comparatively large the objection to the unequal length of coils is not of so great importance.

Where slotted armatures are used the same conditions as just stated apply. It is quite evident that instead of having the conductors placed around the outside of the armature these conductors could be arranged in suitable slots. For instance, in Figure 64, each pair of conductors, such as 1 and 2, 3 and 4, etc., could be placed in separate slots, in which case the same diagram would apply. As there must be an even number of conductors it is plain that there can be an even or odd number of slots, but the number of conductors per slot must be such that the total number of slots times the number of conductors per slot must be an even number.

In Figure 69 is shown an armature similar to the armature previously shown in Figure 64. There are exactly the same number of conductors and commutator segments. The conductors are placed on in the same positions and the connections on the back of the armature are identical with those of the previous figure.

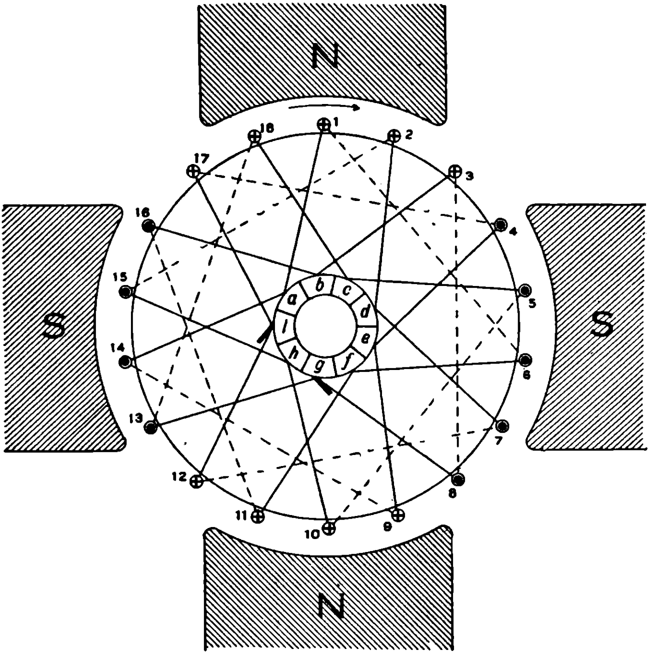


Figure 69.

The distinguishing feature of this armature winding lies in the method of connecting the various coils to each other and to the commutator segments at the front of the armature. Where, in the previously described winding, each coil after making a turn of the armature was carried back to a commutator segment adjacent to the one from which it started, in the present case the end of each armature coil is connected by means of a commutator segment to a coil some distance in advance of it.

The developed winding (Figure 70) clearly shows the manner in which this connection is made. It will be seen that the conductors are so connected that the current induced in each is in the same direction as that in the remaining conductors of the series. It will also be noticed that the developed winding of each element forms a sort of wave and this winding is therefore called a "wave" winding.

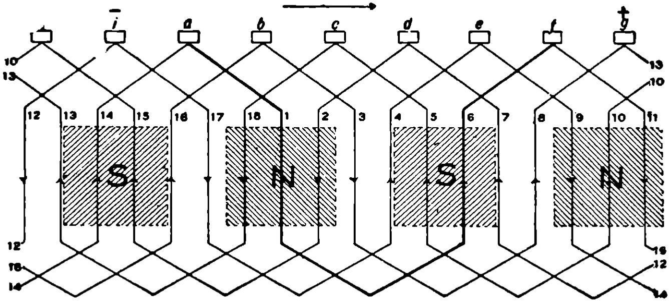


Figure 70.

The scheme previously described may be employed to get a better understanding of this winding. This consists in drawing a circle and dividing it with as many intersections as there are conductors on the armature and then drawing a series of connecting lines through the various points as shown by the winding table. The lines on the outside of the circle are to be considered as representing the rear connections of the armature, and the lines inside the circle the front connections, or those connections running to the commutator segments.

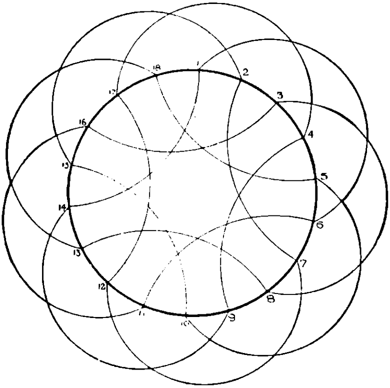


Figure 71.

Figure 71 shows the drawings for the case just described. Tracing out the winding it will be seen that starting from any point and following out the winding circuit every conductor is passed over once and the winding finally returns on itself.

The spacing, or pitch, for the rear is 5, being the same as that used with the lap winding. The spacing at the front of the armature differs from that of the lap winding in that it is not carried back but advances 5 spaces forward. The formula previously used for determining the number of conductors and the spacing may be applied in the present case. $y=\frac{2}{n}\left(\frac{z}{b}\pm 1\right)$. In Figure 69, $n=4$, $z=18$, $b=2$; $y=\frac{2}{4}\left(\frac{18}{2}\pm 1\right)=4$ or 5. For four-pole machines this formula simplified is, $z=4y\pm 2$. In Figure 69, $z=4\times 5-2=18$.

While the front and rear spacings in the drawing shown are alike (5 and 5), it is also possible to have these spacings differ. It is evident that the average spacing must be approximately equal to the total number of conductors divided by the number of poles, as the winding in passing around the armature from one commutator segment to the one next to it comes under each pole piece. In the example shown in Figure 69, this is equal to 4½; the average spacing may therefore be taken as 4, in which case the front spacing could be 5 and the rear spacing 3, or vice versa.

The pitches at the front and rear of the armature must be odd for, as has already been explained, the even-numbered conductors are taken as returns for the odd-numbered conductors.

The winding table for this armature is:

a- 1- 6-f
b- 3- 8-g
c- 5-10-h
d- 7-12-i
e- 9-14-a
f-11-16-b
g-13-18-c
h-15- 2-d
i-17-14-e

Where, in the lap winding there were as many brushes, and as many circuits through the armature, as there were pole pieces, in the winding now under consideration there are only two brushes and therefore only two paths through the armature. The two paths from the negative to the positive brush are:

$$- \left\{ \begin{array}{l} \text{i-17-4-e-9-14-a-1-6-f-11-16-b-3-8-g} \\ \text{i-12-7-d-2-15-h-10-5-c-18-13-g} \end{array} \right\} +$$

It will be seen that one path contains one more coil than the other and, with narrow brushes, only one coil is short-circuited at a time.

CHAPTER IV.

RING ARMATURES.

The ring armature is the oldest and the first to come into practical use. It is especially well suited for high voltage work, where the current used is not of a great quantity. For heavy and variable currents, such as are used in connection with ordinary incandescent lighting it is, however, seldom used. This is principally due to the fact that the resistance of a ring wound armature is about twice as high as that of a drum armature of the same capacity. Full diagrams and views of these armatures are given in chapter on Armature Windings-Diagrams so that we need not take up this branch here but instead can devote ourselves entirely to the practical side of the work.

Let us now consider the application of the wire to the armature. First of all it is necessary to insulate the inside of the slot, where the wire is to rest, with suitable insulating material. As space is an important item it is necessary that the insulation used should be as thin as possible without at the same time sacrificing the necessary strength. It must also be durable, and above all have sufficient heat-resisting qualities, especially if the wire to be used is small in comparison to the currents that are to be carried by it. Suitable insulating materials for this purpose are:

Shellacked paper or cloth.
Shellacked card board.
Thin fiber.
Mica.

Having thus carefully insulated the slot and the ends of the armature where the wire comes to rest upon it we may begin to apply the wire. Figure 72 is drawn to illustrate two methods of doing this. In the first method, shown at *a,* the winding is begun in one corner of the slot and continued in regular order, progressing first from left to right until one layer is finished and then from right to left until the second layer is complete. By this method we can see, by referring to the figure that the last turn of the second layer finally comes in very close contact to the first turn of the first layer. The same condition will exist with every other succession of layers. The result of this is a great liability to abrasion in the first place; further a great liability of the insulation being pierced, should the coil be wound with a great number of turns of wire so that a great difference of potential should come to exist within it. We must in this connection bear in mind that the insulation of armature wires is usually very thin, since space is an important item.

By the above method of winding another great disadvantage is introduced. The lowest coil of wire being so tightly hemmed in, and at the same time there being considerable necessity for handling the wire, the end of which is projecting, there is much risk of breaking it off short. If this actually occurs it becomes necessary to unwind the whole coil in order to get at this wire for repairs.

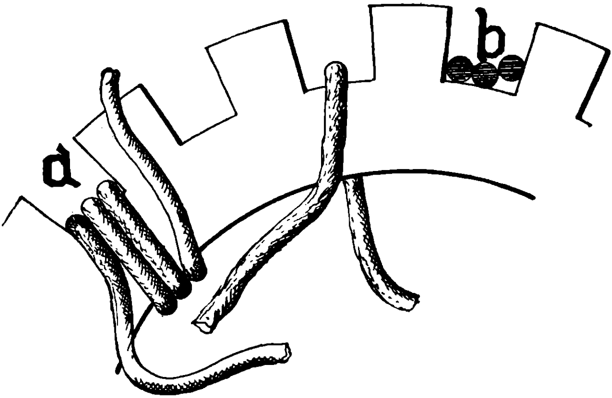


Figure 72.

In order to avoid these elements of trouble the method now to be described is extensively employed: Take of the wire that is to be wound upon the armature sufficient to make one coil; the amount required had best be determined by experiment by first winding a coil temporarily and then unwinding it and marking the middle of it. Take the wire thus marked and place the middle of it exactly in the center of the slot as shown in Figure 72. Now begin winding from the center to one side until that side is filled, next begin winding the other side in the same way and continue winding the second layer in the same way, half from each side, until the slot is filled. By this method if the number of layers is even the two ends of the coil will finish in the center side by side. If there is an uneven number of layers the two ends of the coil will finish at opposite sides. It will make no particular difference which is the case. If the wires come side by side at the finish the full difference of potential will exist between them; if they finish at opposite sides the difference of potential between them will be somewhat less. In either case it will be advisable to provide some insulation between the two halves of the coil.

As we have already seen that the two halves of the armature are in parallel; that is, that the currents from the two halves meet at the positive brush, from there flow out to the line and separate again at the negative brush. If now there are fewer turns of wire on one side of the armature than on the other, or if there is a weak coil, one side will always be generating a greater E. M. F. than the other and consequently current from the high pressure side will always be flowing through the other. To understand this more thoroughly take a glance at Figure 40. In the armature there shown there are 16 coils. If this armature is to generate 40 volts each coil will be called upon to generate an average E. M. F. of 5 volts. Now suppose one of the coils to be cut out of the circuit entirely. It is clear that at all times, except when the dead coil is at the neutral point there are 8 coils generating against 7, i. e. 40 volts against 35. In order to find the current that would flow in such an armature while on open circuit, we subtract the low voltage from the high, which leaves us an active voltage of 5. If the resistance of the armature were .1 ohm we should have a current of 50 amperes circulating in the armature a great part of the time. This would not be a constant current because the position of the dead coil would be constantly changing. While it would occupy a position at or near the neutral point there would be no current and each time after the coil had passed the neutral point the current would be reversed in direction. The current would therefore be changing both in strength and direction. If the dynamo were generating current this condition would not be so marked, but it would nevertheless greatly reduce the capacity of the machine. As the pressure would be variable there would also be a variable current.

Differences in the generation of E. M. F. are sometimes also caused by the wires of different coils being at a greater distance from the center of the armature. Other things being equal the E. M. F. of a coil varies with its distance from the center around which it revolves. It can readily be seen that the farther a wire is removed from the center of the armature, the greater becomes the area which it encloses and the number of lines of force cut by that wire in each revolution. For this reason it is well to select only such methods of winding in which the coils are so arranged that all of them are at the same average distance from the center of the armature shaft. Another cause for differences in the generation is found in inequalities of resistance in different coils. This, however, has no effect upon the armature while it is not delivering current. We have already seen that the loss in potential in any circuit is proportional to the resistance of that circuit and the current flowing in it. To find the exact value of this loss we multiply the two together. If of several coils carrying the same current one has a higher resistance the loss in potential in this coil will be correspondingly greater than in the others. That side of the armature on which such a coil happens to be will therefore have a lower pressure than the other and there will be the same tendency to a vacillating current as in the case of a coil of uneven number of turns. These variations will, however, not be near so great, for an excessive current flowing from the high side will reduce the pressure on that side and the checking of the current on the low side will raise the pressure there so that a balance will be obtained without any great current flow. The main danger of introducing inequalities of resistance in the winding lies in the inner winding with Gramme ring armatures. The space for the winding at this place is necessarily of a different shape than that on the outside and there are also the spokes to contend with.

When the last layer is placed on the armature great care is advisable to see that it finishes off smooth. This adds greatly to the appearance and also avoids churning the air which would be the cause of drawing dust, etc., into the armature.

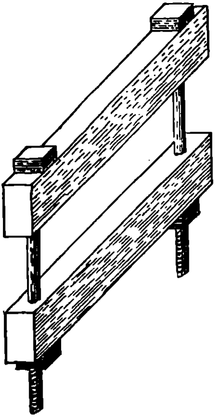


Figure 73.

Care should be exercised to avoid the condition of wires shown at *b* Figure 72. The wire at the right is very likely to work down in time and thus leave loose wire above it that may work down and cause trouble. This would not be near so bad if the space into which it could work were not quite so large so that the wire in question could rest more on the one below it.

If an armature not provided with slots is to be wound it is customary to provide a few clamps, such as are shown in Figure 73, which will hold the wire in place while a coil is being wound. In such a case the space for each coil must be carefully laid off and the clamps placed so that in the end no coil can have more turns than any other.

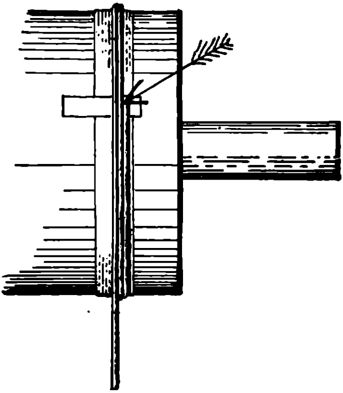


Figure 74.

Before starting the winding, tape should be placed on the armature and left long enough so that it can be used to tie the coils together when the clamps are removed.

In all cases the workman cannot be too careful about locating each wire. Each wire should go to its proper place and by no means cross any other wire below it so as to form a bulge. The strain on the wires of an armature, whether dynamo or motor, is at times very severe, and if there is any flaw it will surely manifest itself.

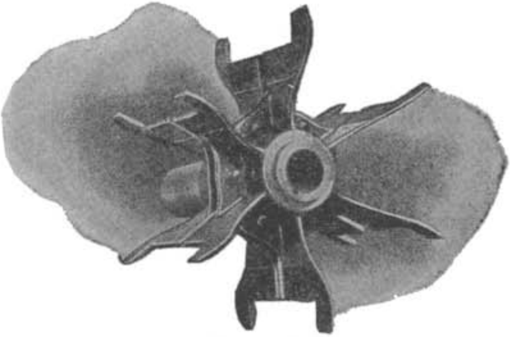


Figure 75.

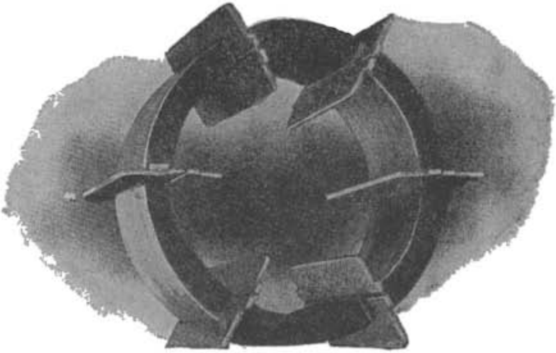


Figure 76.

In the case of a fine winding each layer as it is put in place should be thoroughly soaked with shellac. No current, except of a very low potential from a small battery, should be used either for testing or for any other purpose until this shellac is dry. Shellac until dried is a conductor and may be pierced by the current and thus leave a gap through which at a later time current may leak. An armature of this kind is usually baked at a high temperature for about 24 hours.

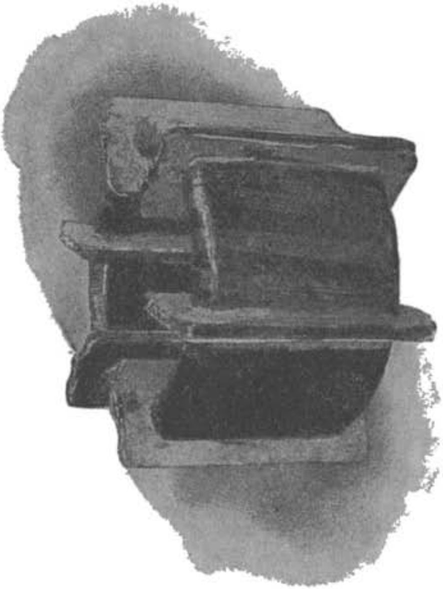


Figure 77.

As an illustration of the great care that is advisable in the insulation of the wires on the armature we may state that some manufacturers place the magnet windings into tanks from which the air can be exhausted

After the air is withdrawn from the coils the insulating compound is allowed to flow into the tank until the coil is submerged. This allows the insulating compound to enter into the most minute openings that may exist between the wires. Air pressure is afterward applied to make certain that the interior of the coil is reached by the fluid.

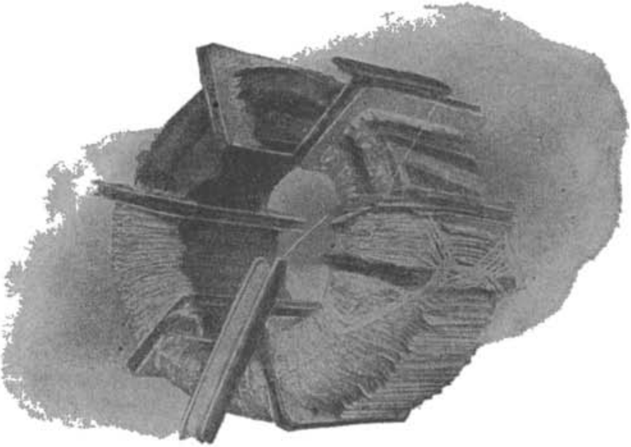


Figure 78.

As each coil is finished it may be tested for correctness of winding by a battery of three or four cells and a small galvanometer. The battery, if always applied in the same way, must produce the same deflections on the galvanometer. See Figure 101. If it does not do this the coil in question has been wound wrong. It is not always necessary to unwind the coil to correct this, as frequently all that will be found necessary is to connect the terminals of the coil in the opposite way from the rest. As this, however, often necessitates the crossing of the wires it is sometimes objectionable.

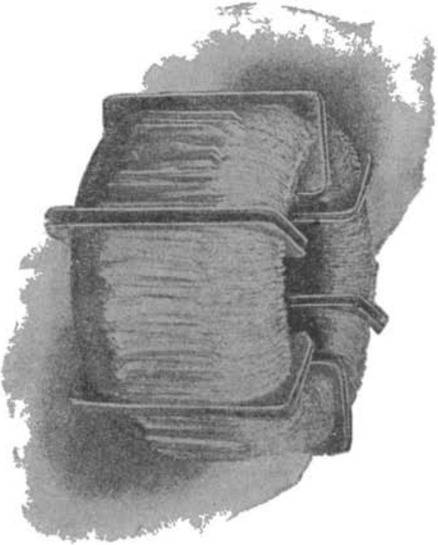


Figure 79.

When all of the coils have been wound upon the armature the end of each coil is to be fastened to the beginning of the next. Both are then fastened to their respective commutator bars. It is well to tape the two wires together; this leaves them stronger to resist mechanical interference and they will then occupy less space. This latter is an important consideration where there are many coils.

The commutator segments are sometimes provided with screws to hold the wire, but oftener the wires are soldered directly to the segments. This latter is the safest method but may cause some trouble should it be desired to remove the commutator for repairs.

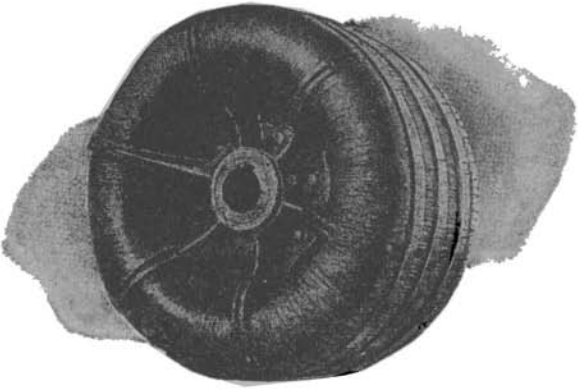


Figure 80.

The next step is the placing of the binding wires. These are to hold the wires of the armature in place and must always be used unless the slots on the armature are of the enclosed, or nearly enclosed, type. The binding wires are wound upon the finished armature as shown in Figure 74. After placing a band of insulating material, such as mica, where the wires are to go, begin by taking one or two turns of wire around the armature with the spool. Draw these as tight as possible and solder as indicated by the arrow in the figure. Now proceed by putting the balance of the turns in place by revolving the armature and holding the wire stationary. In this way the windings can be placed very accurately and close together. After a sufficient number of turns have been put in place they are all soldered together over the whole circumference to avoid the possibility of any of the wires breaking loose and causing damage.

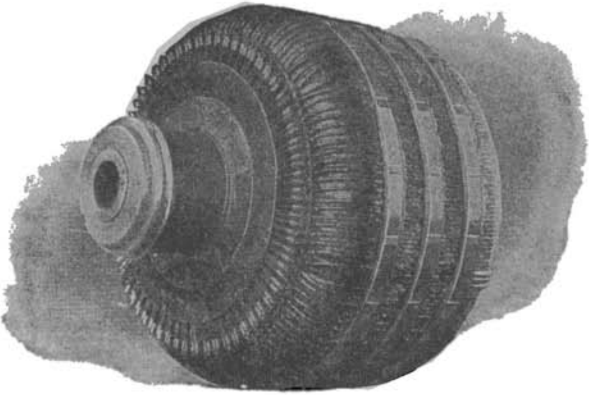


Figure 81.

Where the winding begins and ends a thin piece of brass should be laid under the wire before it is wound on. After the winding is finished this is bent over and soldered. Iron and steel should not be used for binding wires for, although the cross section may not be large, they would always increase the magnetic leakage and that would to some extent lessen the E. M. F. of the machine. The size of the binding wire used ranges from number 20 to number 10; the latter being used for the larger machines and the first for the smaller. Usually about one-third of the armature is covered by these wires.

As an illustration from actual practice in the winding of an armature we refer to Figures 75 to 81 which show the making up of a Wood arc machine armature. Figure 76 shows the laminations assembled with clamps mounted thereon. In Figure 77 the core is insulated and ready for the winding. Figure 78 shows the winding partly finished and it may be noted that the winding is done after the manner described with Figure 72, the wire for each coil being on two separate bobbins one of which is used to wind to the right and the other to the left from the center. Figures 79, 80 and 81 are views of the finished armature. Figure 75 is a view of the spider which, in this case, is not placed in the armature until the winding is completed.

CHAPTER V.

DRUM ARMATURES.

The student of drum armature winding will avoid much worry and mental tribulations if he will at the beginning of his work construct for himself out of a large spool or similar circular object a little imitation armature upon which he can wind with strings such coils as are herein described as being in use on armatures. These little experiments will be even more realistic and instructive if, for this purpose the armature of some real motor or generator, such for instance as a fan motor can be procured. Such an armature should preferably be of the slotted kind as this will facilitate the winding considerably. If a wooden spool such as above referred to is to be used its periphery must be divided off into the proper number of spaces by suitable nails.

A few windings attempted on such spools or armatures will make clear many points that can not easily be grasped in any other way.

One of the simplest forms of armature winding is that shown in Figure 82 and we shall take this for the purpose of demonstration. It will be noticed by reference to the figure that there are twelve slots in the armature and six commutator segments. These commutator segments are not actually shown but are sufficiently indicated by the ends of wires twisted together. Wherever two wires come together there will be, when the armature is finished, a commutator segment. The proportion of two slots to one commutator segment is not always necessary nor desirable as we shall see further along but it is a very convenient one.

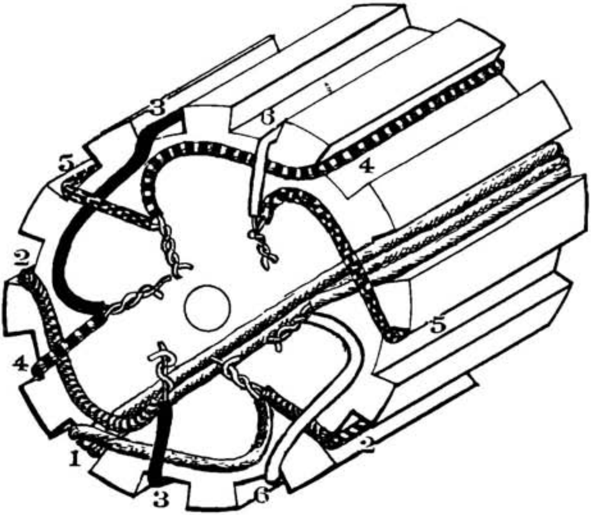


Figure 82.

We may now begin our winding by selecting any one of the slots and starting the wire into this one, continue from it to the one opposite as shown in the figure where the same numbers are used to designate the opposite parts of the same coils. Thus beginning at 1 we wind into this slot, across the back of the armature into the other slot marked 1 and taking as many turns as desired in this way finish this coil by leaving the end of the wire in position to connect to the beginning of the next coil when it is started into slot 2. If we continue to wind in this way we obtain a lefthand winding but as far as the operation of the armature is concerned it is quite immaterial whether we connect to the next coil to the right or the left so long as we continue the armature in the same manner until it is completed.

It will be noticed by tracing out the winding in the figure that each successive coil is started in the 2d slot from the one for which it forms a continuation, that is to say, if the first coil is wound into 1-1 the second must be wound into 2-2, the third into 3-3 etc. It can be readily seen that, as each coil fills out two slots we have in this case with the third coil finished half of the armature. If we were to wind the slots in consecutive order, the connections for our commutator would all come on one side and we could do nothing with our armature. As we now continue in the order we have started we finally complete the entire winding and have the beginning and end of a coil opposite each commutator section. We can now fasten the beginning of the first coil to the end of the last one and if all are connected in the same way this finishes the winding. As we have seen before it will be immaterial whether we progress with these connections to the right or the left so long as we continue throughout in whichever way we have started.

In actual practice only the smallest armatures are constructed with such a small number of coils. As each coil possesses considerable inductance which increases very rapidly with the size of the coil, i. e., number of turns, it is desirable to have as few turns per coil as possible. For a number of other reasons as well, which have been fully set forth under "Current Generation," it is desirable to limit the number of turns of wire per coil.

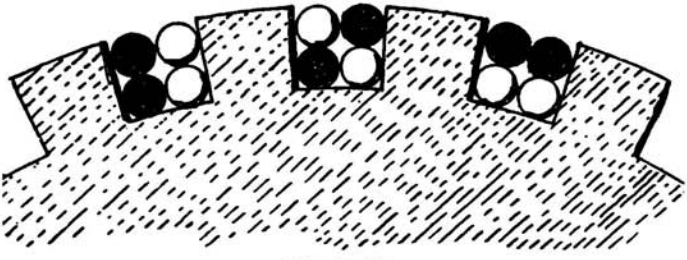


Figure 83.

Now as long as we wind but one coil per slot we shall have the coils needlessly large. It is impracticable to make slots so small that but one or two turns of wire would fill out one of them. The number of coils is limited by the number of commutator segments and unless we wind two or more coils into one slot we can have but half as many commutator sections or coils as there are slots. In order to get small coils it is therefore necessary to place two coils into each slot. This may be accomplished according to either of the plans shown in Figure 83. In this figure the black and white circles respectively represent the wires of two different coils wound into the same slot. As we have already seen under ring armatures that wires of different coils should

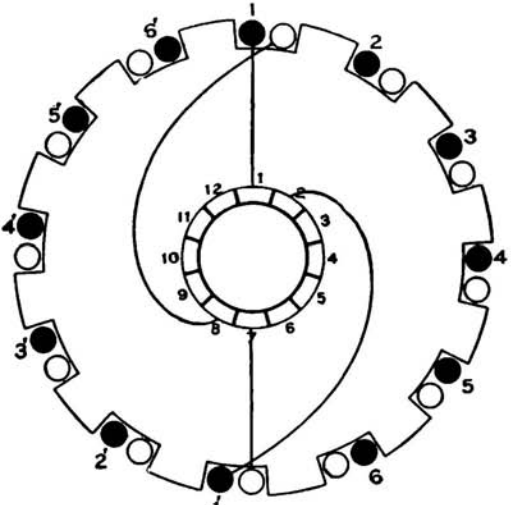


Figure 84.

if possible all be of the same length it follows that the method to the right showing one coil wound over the other should be avoided.

In order to see how two coils are wound into one slot let us refer to Figure 84. This figure is a duplicate of

Figure 82 with the exception that now we have as many commutator segments as there are slots in the armature. The black circles represent the wire of one set of coils and the white those of the other.

The simplest method of winding two coils into one slot consists in first winding one coil complete as before described and then winding the other over it. As this, however, gives two coils of different resistances and also cutting a different number of line of force such a winding is seldom used. A better way is the following: Cut two wires of sufficient length so that each will make one coil, place the armature upon two cross bars of convenient height so that it can be easily turned over when required. Mark all of the slots with appropriate numbers according to the plan of wiring selected so there may be no confusion when the work is started. A very good plan is shown in Figure 85. This plan gives the smallest head of any because there are always two coils running parallel to each other across the ends of the armature. Thus we have three layers of wire crossing over each other where with any of the others we should have six. But in order to get the advantage of this smaller head, we cannot wind the coils in the order given in a previous explanation of this winding. It becomes necessary to wind completely, at the same time, the two coils that run parallel to each other across the ends. To do this requires more experience and forethought than the way previously described. The method is the following: Begin the winding with the coil marked 1, Figure 84, and make one complete turn and fasten the two ends of the wire together, temporarily, if more turns are to follow, or fasten each to its proper place on the commutator if there is to be but one turn. Now turn the armature half way round and wind the other wire in the same way. If there are to be more turns continue to wind the second turn; after this is finished turn the armature back to its original position and wind the first wire again. Repeat in this manner until the desired number of turns in both coils have been obtained. By reference to Figure 84, we note that the windings do not skip slots as before in Figure 82. This is easily explained when it is noticed

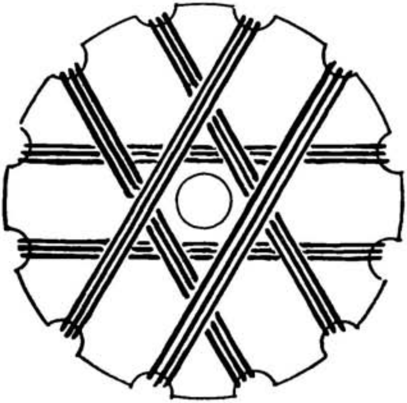


Figure 85.

that each slot contains two conductors and that at each step we skip one conductor or coil as before.

It is not necessary in actual practice to turn the armature around as above suggested. This was suggested merely as a beginning to make the principle more plain. The same result can readily be obtained if the armature is left stationary. The only point that it is necessary to observe is that the windings must come right to connect to the commutator as shown in the figure.

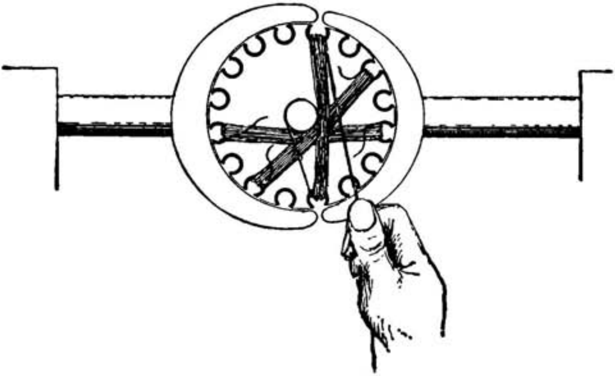


Figure 86.

It is well enough to observe care and see that all of the coils are wound in the same direction but it will make no material difference in the operation if one part of the coils are wound left hand and the other right. The essential point is to see that they are connected so that the magnetism resulting from current flow through the coil will be the same in all. If this is different in one coil than it is in the others it can easily be rectified by changing the end connections of the coil in question.

While hand winding is the only method possible with ring armatures many of the smaller drum armatures may be wound with the aid of machinery. As this machinery is very simple and can be rigged up almost anywhere we give in Figure 86 an illustration of one of the methods used. In this figure the armature is shown from one end. It is fastened between two metal clamps which hold it rigidly and which are mounted in bearings so that they can be revolved when desired. This arrangement admits of winding such an armature much in the same way as a spool of wire would be wound. There are extending flanges on the two clamps for the purpose of protecting the wire from being entangled in the shaft which projects from both ends of the armature. When one coil is wound the armature must be turned a little to admit of winding the next coil.

The majority of the larger dynamos and motors are now made multipolar and in connection with these a method of winding entirely different from that heretofore treated is generally used. While it is perfectly possible to use an armature wound for a bi-polar machine in connection with a multi-polar one it is not customary nor advisable to do so. The coil of a multi-polar dynamo, as a rule, does not encircle the whole armature but instead covers only a part of the periphery. In general such coils have their return wire spaced about as far ahead or behind the first turn as it is from the center of one pole piece to the center of the next one. This it can readily be seen gives us a winding of much lower resistance since we have not the amount of dead wire at the ends. Furthermore it makes the magnetic circuit much better and lessens the reaction. And lastly it makes possible the use of much larger diameters of armature than would be practicable with the old style of winding.

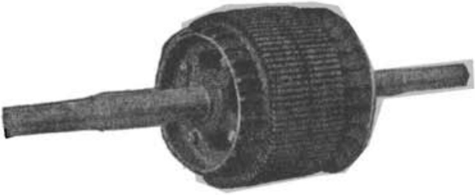


Figure 87.

Another great advantage of this style of armature is, that it becomes possible to use the so-called "former coils" in connection with them.

A former coil, as the name implies, is one that is wound complete upon a former, independent of the armature, and placed upon it afterward. Figures 87, 88 and 89 show a general view of a former coil and the method of placing it on the armature, Figure 87 showing the armature core without winding, Figure 88 the formed coil and Figure 89 the completed armature. Figures 90, 91 and 92 illustrate the manner in which formed coils are made up.

In Figure 90 the black circles represent strong pins fastened into a piece of plank or other suitable material. The wire is wound around these pins as indicated in the figure; as many turns being taken as we have decided to allow for each coil. When the coil is thus completely wound, it is taken from the pins, and the lower ends placed in a suitable clamp as indicated by the broken line and in the center of the figure. After this clamp is fastened onto the coil, the two halves of the coil are spread apart, one being pulled toward the operator and the other being pushed away from him at

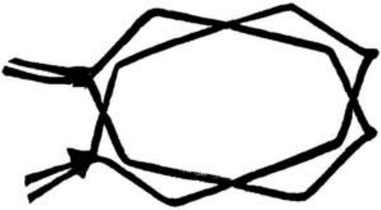


Figure 88.

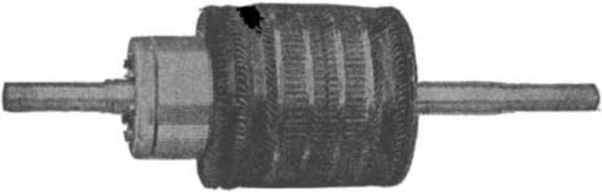


Figure 89.

right angles to the clamp. In this way the coil is made to assume the shape illustrated in Figure 94. Before winding a coil in this manner it is of course necessary to know just what length and breadth it must be and a pattern coil must therefore first of all be prepared from which the spacing of the pins can be taken so that the completed coil will fit into the slots for which it is intended.

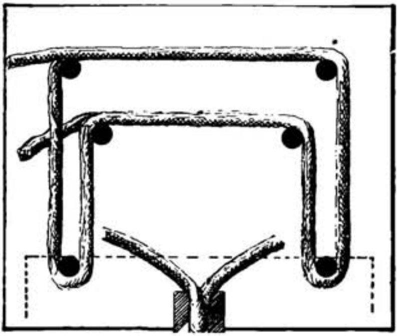


Figure 90.

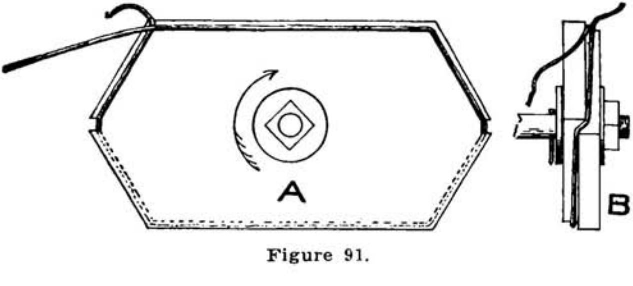


Figure 91.

The arrangement shown in Figure 91 is made up of two boards loosely laid together and the coil is formed upon it by revolving the frame and letting the wire wind upon it. When a coil is finished the front half of the frame is removed and the coil taken off. At A, a front view of the frame is given and at B an end view. It is necessary to make up a frame of this kind for every style of coil but when this is once made coils can be very quickly wound upon it.

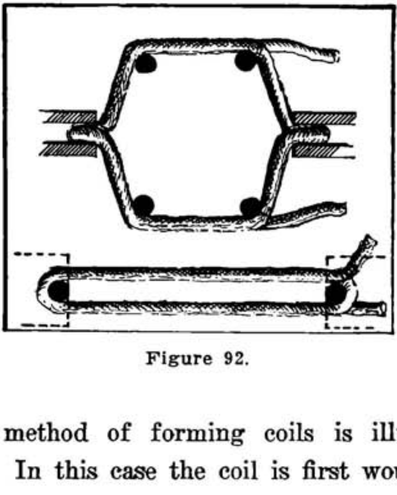


Figure 92.

Another method of forming coils is illustrated in Figure 92. In this case the coil is first wound around two pins as shown in the upper part of the figure. The ends are then placed in two clamps as indicated by the dotted lines at the top and shaded lines in the center of the figure. After these clamps are fastened, the coil is turned one-fourth around, and the wires spread out over the four pins as indicated in the figure.

It will be noticed that the manner of forming results in coils of two different shapes. One of these, Figure 92, is known as a "barrel" winding and an armature wound with such coils has the general appearance depicted in Figure 93. The other is known as the "evolute" winding and when placed upon an armature shows as in Figure 94.

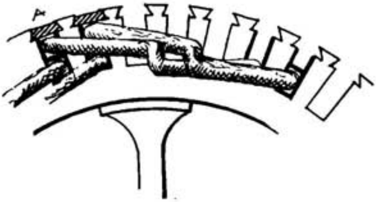


Figure 93.

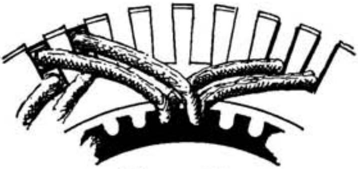


Figure 94.

When all of the coils are once wound the placing of them upon the armature is a very simple matter. After the slot has been insulated in the usual manner we begin at any slot that is convenient and lay in the coils as shown in Figures 93 and 94, continuing until all of the slots are filled. Before we can fill all of the slots it will be seen that it becomes necessary to raise up some of the first ones and insert the last ones below them. In this way the whole armature is completely and regularly filled out.

There is no difference of importance between the evolute and the barrel winding and there is no reason whatever why one style cannot be used on one side of the armature and the other on the opposite side.

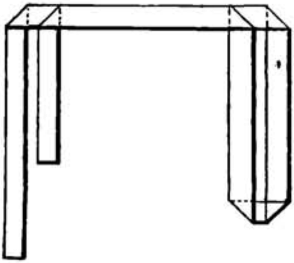


Figure 95.

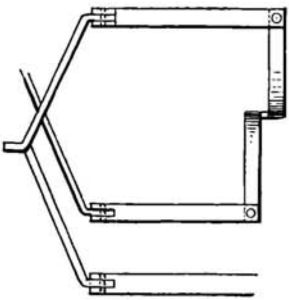


Figure 96.

For very large machines the coils often consist of single bars of copper made of special dimensions to suit the requirements. These are often arranged as shown in Figures 95 and 96. Such bars are sometimes uninsulated and laid into the slots with insulation loose on the sides and bottom and between the different bars of a slot. Such bars are often held in place by pieces of wood slipped into the slots as indicated at Figure 93. Where no provision for the insertion of such strips of wood has been made the bars are held in place by the regular binding wires.

Where the formed coil consists of several turns of wire it is usual after removing from the form to cover the coil over its entire length with cotton tape. As the placing on of the tape by hand would be a slow procedure machines are generally used for this purpose. These machines are so constructed that a roll of tape placed on a split metal ring is revolved around that wire to be taped, the wire being gradually moved until it is entirely covered.

DIPPING AND BAKING OF ARMATURES

The dipping of armatures fills all pores, makes wires rest more solidly against one another, excludes moisture and increases insulating strength. To prepare for dipping clean away all dirt, protect polished parts. Dip in vertical position for at least thirty minutes and watch for air bubbles. As long as these rise the work is not complete. If no tank for vertical dipping is available, dip in tank and turn armature from time to time; keep each part under varnish at least thirty minutes. Always drain in vertical position. To drain and bake in horizontal position may cause some unbalancing which may be serious if machine is to be run at a high rate of speed.

If varnish is at a greater specific gravity than 0.85 at about 60 F. or 0.84 at 85 F. it should be thinned to this with benzine. The baking should take from 24 to 48 hours according to size of armature and the temperature should not exceed 275 F.

CHAPTER VI.

COMMUTATOR CONSTRUCTION.

The general principle of commutator construction is illustrated in Figure 97. The commutator consists partly of an iron core mounted upon a shaft and fastened thereto by keys, set screws, or by shrinking on, or fastened directly to the armature core. It is preferable to have it so arranged that it can be readily removed for repairs or turning down. The latter operation, if the machine operates at a high rate of speed becomes necessary quite frequently, especially if the brushes are not well kept in order. Very often, however, the turning

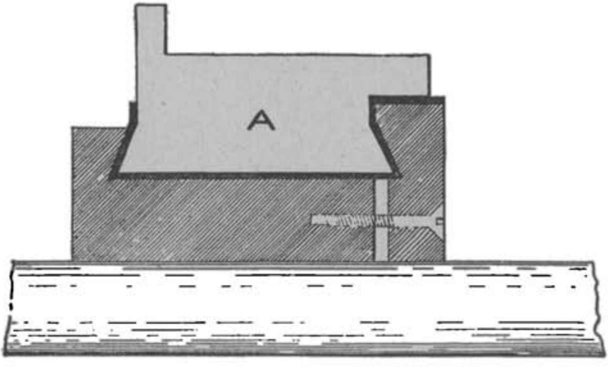


Figure 97.

down is done without removing the commutator or the armature by making arrangements so that the turning tool can be adjusted to the machine.

The manner of fastening the copper bars to the iron core can be seen in Figure 97, the heavy black lines representing the insulation and the wedge shape of the copper and corresponding form of the iron being especially suitable to hold both together when the screws are drawn up. A portion of the front view of the same commutator is given in Figure 98. It is of the utmost importance especially with high speed machines that the commutator be perfectly true and smooth. If this is not the case the brushes are apt to leave the surface for an instant after passing over the high places. This will result in some sparking which will soon eat away parts of the copper.

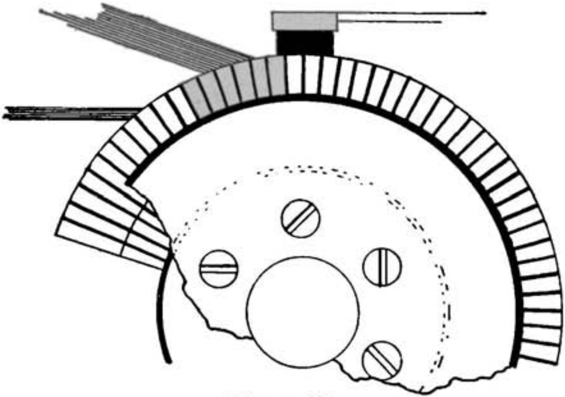


Figure 98.

As the insulation must be provided between each of the bars and as these are usually of a great number it is very important that the insulating medium should be hard enough so as not to be very much compressed by

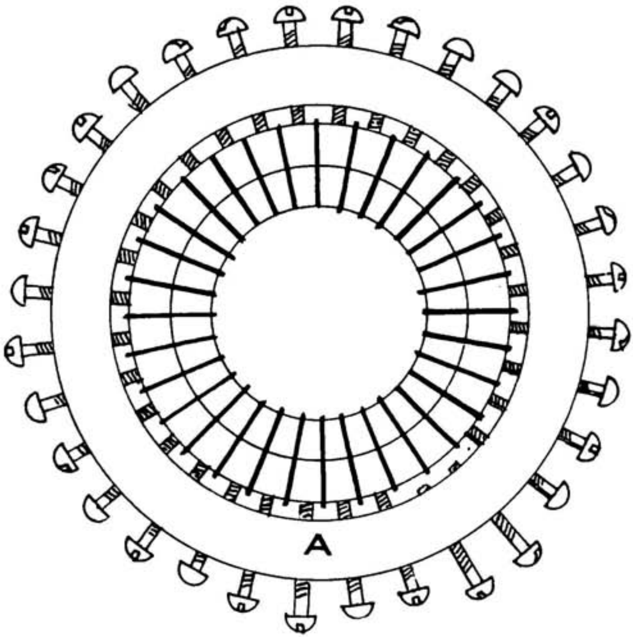


Figure 99.

the pressure applied to bring the bars into place. It should also be fire proof and not subject to much expansion or contraction as otherwise the parts are likely to become loose. These requirements are best answered by mica and this is used almost entirely. Various special kinds of copper are generally used for the bars.

In assembling the commutator bars a cylindrical piece of wood of the diameter of the inside of the commutator is mounted in an upright position on a wooden platform or table. The commutator segments and the insulating material between the segments are then placed around this wood pattern and held in place by an adjustable band or rope. When all the segments are in position a metal ring such as is shown in Figure 99 is placed over them. The screws are set up so as to make the whole as near circular as possible. The whole device is now placed in an oven and baked for some time after which it is removed and the screws again set up as tight as is practicable. It is now placed in a lathe and the inside and ends of the commutator turned down to the desired shape. The core is now inserted and fastened in place and the ring removed and the outside face finished off smooth and round. Various other devices similar to the one described are also used for this purpose.

The size of the commutator varies with the voltage and the ampere capacity of the machine. If there is not sufficient copper in the bars they will be overheated by the current; if there is not sufficient insulation between them the current is likely to jump across. Of course the higher the voltage per bar of the machine the greater the danger from this.

The brushes may be of copper or carbon. Carbon brushes are generally set as shown at the top of Figure 98. If arranged in this manner they need not be changed for a change in the direction of rotation of the armature. Copper brushes are set on as shown at the left of the figure. In case the machine is to be reversed the brushes must also be reversed. Either copper or carbon brushes may be arranged to cover several commutator bars. It is, however, not safe to cover several bars with a brush in all machines. Many machines would be ruined thereby.

The size, or contact surface of the brushes must be proportional to the current. As a general rule from 30 to 40 amperes per square inch are allowed with carbon brushes and about 150 with copper. As the resistance of carbon is so much higher it is often arranged to have a brush consist of part carbon and part copper, the combination being effected in various ways either by forming copper wires directly in with the carbon or attaching them to the surface of the carbon. It is customary to divide brushes into several sections all electrically connected to each other but mechanically independent. This brings about much smoother and better operation, since a rough spot on the commutator will now affect only one of the sections where otherwise it would throw the whole brush out of contact.

It is also advisable to stagger the brushes as shown in Figure 100 and to provide considerable lateral play for the shaft. This will secure an even wear of the greater part of the commutator surface. If the commutator is rough it can be smoothed with sandpaper; emery paper must not be used for this purpose as the fine particles are apt to lodge in the insulation and cause short circuits.

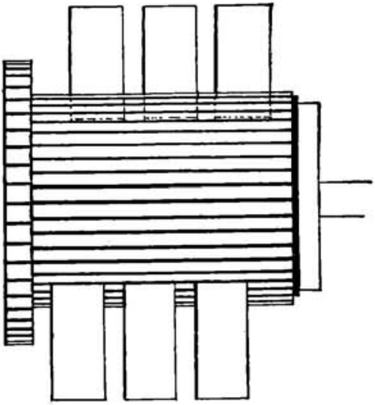


Figure 100.

If the carbon brushes do not fit well they are often trued by placing a piece of sandpaper rough side up on the commutator so that it can be drawn back and forth. This will cut the brush to the exact shape of the surface of the commutator under it.

CHAPTER VII.

ARMATURE TROUBLES.

Armature troubles may result from any one of the following causes:

There may be a wrong connection of one or more of the coils.

Some of the coils may be grounded.

There may be an open circuit.

There may be a short circuit.

The brushes may be improperly set.

There may not be sufficient area of contact between the brushes and the commutator.

The commutator may be rough and uneven.

The fields may be of uneven strength.

The test for a wrong connection of coils may be best explained by reference to Figures 101 and 102. These figures show part of the coils of a ring armature. If a battery or other source of E. M. F. be applied in Figure 101, as indicated by the signs, considerable current will flow through the coil which is directly connected to the two commutator segments to which the battery is connected. There will also be a current flow through the other coils of the armature, but this current, as it must pass through so many more coils, is of course much weaker. An inspection of the two figures will show clearly that if a coil is connected right as shown in Figure 101 there will be conflicting fields set up, as

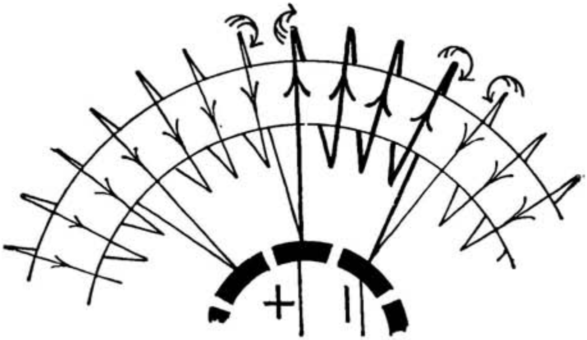


Figure 101.

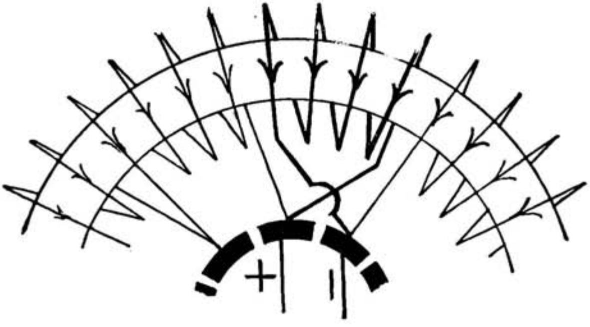


Figure 102.

indicated by the arrows and these will deflect a compass needle brought near them in a certain definite way. If now the compass needle be mounted at the proper distance from the armature and connections are made to all of the coils in rotation, these deflections must, if all of the coils are wound in the same way, be the same for each coil as it is brought in position before the needle. If one of the coils is connected wrong, as indicated in Figure 102, there will be no conflicting fields and the deflection of the compass needle will be of an entirely different nature.

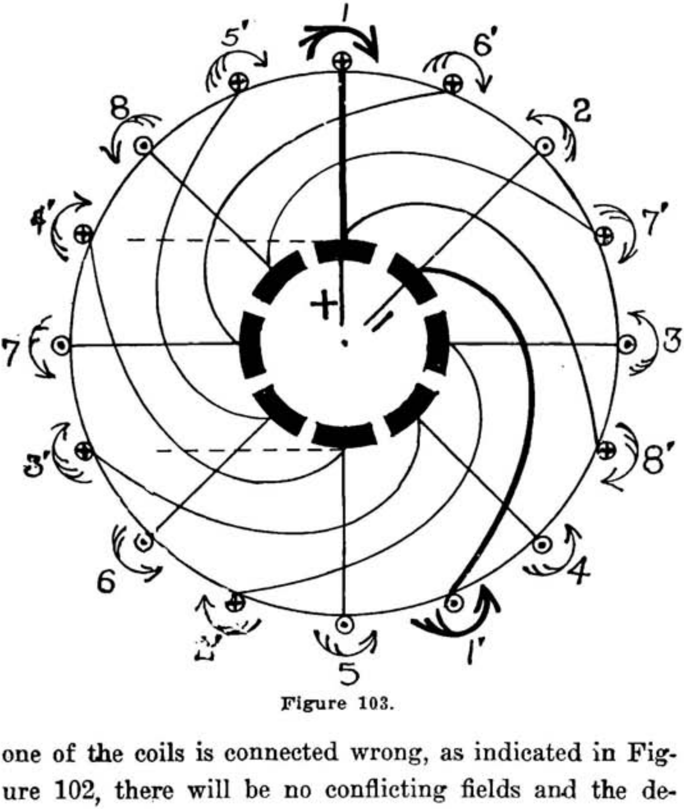


Figure 103.

The same principle can be applied to the testing of drum armatures for wrong connection of a coil. In Figure 103 the heavy black lines indicate the coil that is getting the greater part of the current, and the arrows drawn in connection with all of the wires indicate the direction of the lines of force produced, and consequently the conflicting fields set up by the current flowing in the coil.

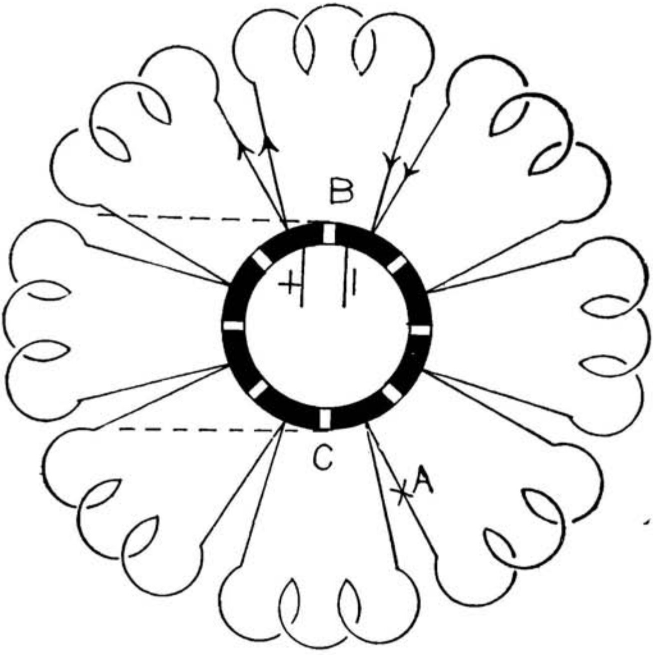


Figure 104.

Figure 104 will aid in making plain the wiring of an armature. This figure shows the wiring of either a ring or drum armature just as it would be if the wire were all taken off the core without detaching it from the commutator and spread out so as to admit of inspection of the wire used. It will be seen that the greater the number of commutator sections there are upon any armature the nearer must the total current used flow through the one coil that is directly in connection with the source of supply. If, for instance, there are 100 coils 99 per cent of the current will flow through the one coil.

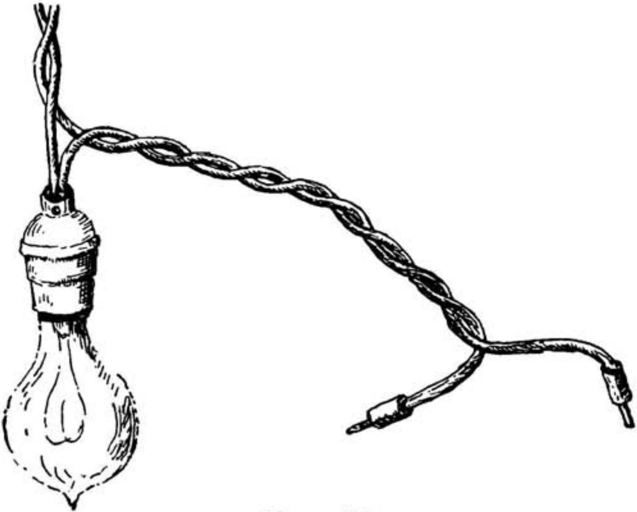


Figure 105.

The test for grounded coils is made by simply connecting one pole of a battery or electric light circuit to the iron of the armature and the other to any one of the commutator segments. If the connection is made as in Figure 105 the lamp will light if the insulation between the coils and the iron is broken down. The exact spot where the defect exists can be located only by a search, and it may be necessary to disconnect all of the coils from the commutator and test them one by one.

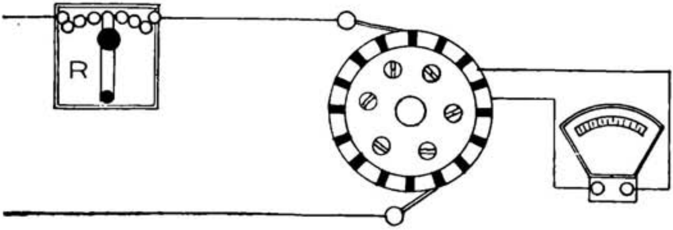


Figure 106.

An open circuit can be located by the method shown in Figure 106. A voltmeter is applied to adjacent sections of the commutator as indicated at the right of the figure. Current is next applied to the armature as shown by the two brushes at top and bottom. By means of the rheostat this current is regulated until a noticeable deflection upon the voltmeter is obtained. If the voltmeter connections are now made in rotation to all of the segment, about the same deflection will be obtained from all of them on that side of the armature which is sound. Upon the other side, however, no deflection will be obtained until the segments between which the broken coil is located is reached; at this point the voltmeter reading will be much higher. This can be made a little more clear by reference to Figure 104. Suppose the wire to be broken at A, and the battery connected as shown by the dotted lines: It is clear the current will flow in the coils at the left and this current will give only a small reading on the voltmeter because a coil of the armature which has a very low resistance is in shunt with it. When we come to the other side and find the broken coil however the only current that passes is that through the voltmeter, and therefore the reading on it will be about as high as that which is obtained by connecting at B and C.

If instead of an open circuit we have a short circuit we can proceed in the same way, but instead of an increased reading when we come to the defective coil we shall obtain no reading at all. A short circuit is very often due to two grounds, and it is advisable in all cases of trouble of this kind to first see that the armature is clear of grounds before testing for other faults.

Figure 107 shows a very handy device for the rapid testing of armatures. A single field magnet with its winding is mounted in an upright position. Two standards are arranged so that the armature, which is mounted on its shaft, can be easily revolved in a position close to the field magnet. An alternating current is passed through the magnet winding. In testing for short circuits the magnet is slowly revolved and a piece of iron or steel held close to the armature on the side away from the field magnet. If there is a short circuit in the armature winding, this winding will act as the secondary of a transformer and current will be induced in it which will magnetize the armature and cause the piece of metal to be drawn to it. If the armature is free from short circuits the piece of metal will not be vibrated.

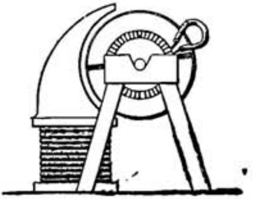


Figure 107.

To test for open circuits the armature is again revolved and each commutator segment is short circuited by a short piece of wire with the adjacent segment. Each time this short circuit is put on the small piece of iron held in the hand will vibrate. If the armature winding is open between any two segments this will be indicated by the failure of the iron to vibrate.

The E. M. F.'s induced in the two sides of an armature are not always exactly alike and this results in useless currents circulating in the coils. Such unbalancing may be due to differences in the strength of pole pieces; to differences in the air gap or to unsymmetrical winding which results when the number of coils is not a multiple of the number of paths. To reduce the heating from such current equalizing bars are run from theoretically equal potential points. Such connections are usually made at the back of the armature.

CHAPTER VIII.

ARMATURE CALCULATIONS.

The accurate design of a new type of dynamo is as much a matter of experiment as it is of calculation. There are so many factors involved that cannot be accurately determined until the machine of the exact proportions contemplated has been tried. These factors are, the permeability of the iron; the reluctance of the magnetic circuit; the tendency to leakage of the lines of force; the reaction of the armature; the proportion of the "dead wire"; losses due to foucault currents and to hysterisis.

It is not that the manner in which these losses may be increased or decreased is not well enough known, but simply that their exact values cannot be predetermined with any great degree of accuracy.

For this reason it is always necessary to allow for a considerable range of variation so that if we fall short or run over in any of the factors we can compensate by some other of these factors and finally obtain exactly what we seek.

In general practice all of this compensating is done through the agency of the field current strength, and for this purpose some means of regulating the current strength used in the fields is resorted to. In all self-exciting machines this is done by means of a resistance, variable at the will of the operator, which is placed in series with the field magnet winding. An increase in this resistance brings about a reduction in the current flow through the fields and a consequent lessening of the lines of force of which the field is made up which in turn causes a decrease in the voltage of the dynamo.

A variation in speed of course also brings with it a corresponding variation in the voltage generated and in many cases this is resorted to. This is a very convenient method when one has free hand in this respect, but very often no choice in this regard can be allowed. In any case this method can be used only in a general way and the current regulation mentioned above must be provided to make up for the continual variations due to change of load, etc., that occur daily. When a new machine is built it is, however, perfectly proper to arrange that it shall run at the speed at which it produces the required voltage unless of course it is to be attached to some shaft or engine which determines the speed at which it shall run.

The main precaution that is necessary to observe in arranging a dynamo so that the regulation of the voltage shall be accomplished by means of variation in the field current strength is to see that the field magnets are not worked at too high a degree of saturation. We have seen in previous chapter that the effect of the current in producing magnetism differs very much with different degrees of saturation and that with a high degree of saturation a great variation of current strength is necessary to increase the magnetism to an appreciable degree. It follows therefore, that in order to make the magnetism as sensitive as possible to current changes, we must use our iron at a low degree of saturation. By doing this we shall need to make but slight changes in the strength of the current to affect our machine in the way we desire.

If, however, we provide too much iron, we shall be adding considerable unnecessary expense so that in the last resort, unless we have already constructed very similar machines out of the same material and along the same lines we are driven to experiment.

In view of the above the following formulas are given merely as an aid in experimentation. They will serve very well to impress the student in the manner in which a variation of the different factors can be made to effect the final result. They will also come very useful when it is desired to learn how best a given machine may be changed in order to give certain results.

In connection with the following formulæ we shall adopt the attached set of symbols:

Let

F=the total number of lines of force or flux.

V=the number of volts to be generated.

S=the number of slots in the armature.

R. P. S.=the number of revolutions per second.

W=the number of wires per slot.

Then to find the number of wires necessary per slot where the speed and the flux are fixed we have:

$$W=\frac{10^8\times V}{F\times S\times R.P.S.}$$

To find the speed where the flux and the number of wires are fixed:

$$S=\frac{10^8\times V}{F\times W\times R.P.S.}$$

To find the necessary strength of field where the wires and speed are fixed:

$$F=\frac{10^8\times V}{W\times S\times R.P.S.}$$

To find the volts generated:

$$V=\frac{F\times W\times S\times R.P.S.}{10^8}$$

In actual practice whenever a new dynamo or motor is to be constructed it is, so to speak, built up around the armature. That is to say, it is usual to first design the armature and then the other parts can be made to fit around it. The principal factor to be taken into account is the size of the wire to be used. In order to deliver a certain current, the number of poles, etc., being fixed, we must use a certain size of wire. While we are not precisely bound to a certain size of wire, still economy demands that we keep very close to it. In most cases the heating of the wire is the governing consideration although in many cases it is the drop of potential at the terminals that governs. With reference to either of these considerations the smaller the wire the greater is the heating and the loss in potential. If we, therefore, wish to be economical in the construction of an armature we must know very nearly what to expect from a given current and a given wire. We can always keep on the safe side in either case by using larger wire than is absolutely necessary but as this not only adds to the cost for wire but necessarily increases the dimensions of the whole machine, or at the least the speed, it is essential that this point be carefully worked out.

Since, as we have already seen, there are quite a number of factors in armature construction that can be varied, to find the proportions best suited for any given case will very likely require a number of trial calculations.

As an example, let us now take an armature 8 inches in diameter and 8 inches in length and see what it will do for us. Such an armature has a cross section of 64 square inches and assuming a flux of 30,000 lines per inch we have a total flux of 1,920,000 lines through the armature. Our next step is to find how many times one wire must cut this number of lines of force to generate the required voltage, which we will say is 110. For this purpose we first divide 110 times 100,000,000 (which is the total number of lines to be cut per second) by the total flux

1,920,000 and obtain as the result 5,728. After this, in order to find the necessary number of wires to be placed upon the armature, we divide this (5,728) by the number of revolutions the armature makes per second. If our armature revolves at the rate of 20 turns per second (1,200 per minute) we shall need one-twentieth of 5,728 wires placed upon it. This is equal to 286. As the armature, 8 inches in diameter, has a circumference of 25.12 inches this gives us a wire running about 11 to the inch. If there is to be but one layer we shall need a number 12 wire. As the two sides of the armature are in parallel we have according to Table I a capacity of 2 times 14.31. If instead of one layer we decide to use two we can use number 6 wire with 5.5 turns per inch, which will give us a capacity of 56.56 amperes.

It may be stated in explanation of the calculations here made that each wire in the course of one revolution cuts the total flux two times; but as the two halves of the armature are in parallel each side must produce the full voltage of the machine.

The question of how much current can be allowed in a given wire requires some study. It depends to a great extent upon the manner in which the armature is to be used. The heating in any wire is proportional to the square of the current used. During the time that no current is passing the heat is of course rapidly dissipated so that if an armature is used intermittently we can subject it to a much greater current than would be possible if it were in use continually.

All calculations of current carrying capacity must be based upon a certain radiating surface per unit of energy consumed. The greater this radiating surface the less will be the heating. The amount of radiating surface allowed in armatures varies from one square inch per watt to three square inches. About 1.75 will insure a cool operating armature.

In the attached tables I and II the carrying capacity of the different wires is given. These tables are figured from the formula $I=\sqrt{\frac{rs}{a \times R}}$, r. s. being the radiating surface and R the resistance of a unit of wire under consideration. In the formula a stands for the amount of radiating surface in square inches per watt we desire to have. In table I it stands for 3 and in table II for 1. This formula gives the current allowed where the wire is wound in one layer. As we add more layers we must with each successive layer reduce the current so that the watts consumed shall be always the same. No matter how many layers deep we may wind an armature we do not appreciably increase the radiating surface, therefore in order to keep the proportions of energy and emissivity the same the watts must remain the same.

Since $I^2 \times R$ equals the watts permissible in one layer, and since two layers have double the value of R, for a depth of two layers I^2 must be only half of what it

TABLE I.

Table showing current carrying capacity of different wires at different depths of winding, 3 sq. in. radiating surface per watt.

B. & S. Gauge.	Diameter bare.	Resistance per foot 140° F.	Diameter D. C. C.	Amperes at different depths of winding layers.						Number of wires per inch.	I^2
				1	2	3	4	5	6		
4	.2043	.000283	.224	56.28	39.74	32.42	28.12	25.15	22.97	4.45	3166
5	.1819	.000357	.200	47.30	33.46	27.33	23.66	21.16	19.31	5.00	2240
6	.1620	.000450	.180	40.00	28.28	23.08	20.00	17.88	16.34	5.5	1600
7	.1413	.000567	.158	33.40	23.60	19.28	16.67	14.93	13.63	6.3	1114
8	.1285	.000715	.144	28.35	20.04	16.37	14.17	12.68	11.57	7.0	805
9	.1144	.000902	.130	24.00	16.97	13.85	12.00	10.72	9.74	7.7	576
10	.1019	.001137	.117	20.27	14.31	11.70	10.14	9.05	8.24	8.6	411
11	.0907	.001436	.106	17.19	12.12	9.69	8.60	7.68	7.00	9.6	295
12	.0808	.00181	.093	14.31	10.09	8.24	7.14	6.40	5.83	10.7	205
13	.0719	.00228	.084	12.12	8.54	7.00	6.08	5.38	4.89	11.9	147
14	.0640	.00288	.075	10.19	7.21	5.91	5.09	4.58	4.12	13.8	104
15	.0570	.00362	.067	8.60	6.08	4.95	4.30	3.87	3.50	15.0	74
16	.0508	.00458	.059	7.14	5.04	4.12	3.57	3.19	2.91	17.0	51
17	.0452	.00575	.053	6.08	4.30	3.5	3.04	2.64	2.47	19.0	37
18	.0403	.00727	.048	5.09	3.60	2.94	2.54	2.28	2.08	21.0	26
19	.0358	.00916	.044	4.36	3.08	2.52	2.18	1.97	1.78	22.7	19
20	.0319	.01153	.040	3.74	2.64	2.16	1.87	1.67	1.52	25.0	14
21	.0284	.01454	.036	3.14	2.22	1.81	1.57	1.39	1.28	28.0	9.9
22	.0253	.01845	.033	2.66	1.87	1.54	1.33	1.19	1.09	30.3	7.1
23	.0225	.0231	.030	2.28	1.61	1.30	1.14	1.01	.94	33.3	5.2
24	.0201	.0295	.028	1.94	1.37	1.14	.97	.86	.80	35.7	3.8
25	.0179	.0365	.026	1.70	1.18	.98	.85	.80	.74	38.4	2.9
26	.0159	.0461	.024	1.41	1.00	.82	.71	.63	.57	42.0	2.0
27	.0142	.0603	.022	1.18	.78	.68	.59	.52	.47	45.5	1.4
28	.0126	.0744	.021	1.04	.72	.60	.52	.47	.42	48.0	1.1
29	.0112	.0925	.020	.93	.65	.52	.46	.42	.38	50.0	.86
30	.0100	.1181	.018	.77	.54	.44	.38	.35	.31	56.0	.91

TABLE 11

Table showing current carrying capacity of different wires at different depths of winding, 1 sq. in. radiating surface per watt.

B. & S. Gauge.	Diameter bare.	Resistance per foot 140° F.	Diameter D. C. C.	Amperes at different depths of winding layers.						Number turns per inch.	I^2
				1	2	3	4	5	6		
4	.2043	.000283	.224	97.36	68.75	55.88	48.64	43.50	39.73	4.45	9498
5	.1819	.000357	.200	81.82	57.88	47.27	40.87	36.60	33.40	5.00	6720
6	.1620	.000450	.180	69.20	48.92	39 92	34.60	30.93	28.28	5.5	4800.
7	.1413	.000567	.158	57.78	40.82	33.35	28.91	25.86	23.60	6.3	3344
8	.1285	.000715	.144	49.04	34.66	28.37	24.57	21.97	20.07	7.0	2416
9	.1144	.000902	.130	41.52	29.37	24.00	20.76	18.60	16.97	7.7	1728
10	.1019	.001137	.117	35.06	24.81	20.27	17.54	15.71	14.35	8.6	1233
11	.0907	.001436	.106	29.74	21.02	17.17	14.86	13.30	12.12	9.6	885
12	.0808	.00181	.093	24.79	17.52	14 31	12.40	11.09	10 09	10.7	615
13	.0719	.00228	.084	21.00	14.86	12.12	10.50	9 38	8.54	11.9	441
14	.0640	.00288	.075	17.66	12.49	10.19	8.83	7.88	7.21	13.3	312
15	.0570	.00362	.067	14.89	10.53	8.60	7.44	6.66	6.08	15.0	222
16	.0508	.00458	.059	12.40	8.77	7.21	6.20	5.56	5.09	17.0	154
17	.0452	.00575	.053	10.53	7.44	6.08	5.26	4.71	4.30	19.0	111
18	.0403	.00727	.048	8.88	6.28	5.12	4.44	3.97	3.63	21.0	79
19	.0358	.00916	.044	7.54	5.34	4.35	3.76	3.37	3.08	22.7	57
20	.0319	.01153	.040	6.49	4.58	3.74	3.24	2.89	2.64	25.0	42
21	.0284	.01454	.036	5.38	3.80	3.11	2.68	2.40	2.19	28.0	29
22	.0253	.01845	.033	4.58	3.24	2.64	2.28	2.04	1.87	30.3	21
23	.0225	.0231	.030	4.00	2.82	2.30	2.00	1.78	1.64	33.3	16
24	.0201	.0295	.028	3.37	2.38	1.94	1.67	1.51	1.37	35.7	11.4
25	.0179	.0365	.026	2.93	2.07	1.67	1.44	1.30	1.18	38.4	8.6
26	.0159	.0461	.024	2.49	1.76	1.44	1.22	1.09	1.00	42.0	6.2
27	.0142	.0603	.022	2.07	1.44	1.18	1.04	.94	.84	45.5	4.3
28	.0126	.0744	.021	1.78	1.26	1.04	.89	.78	.71	48.0	3.2
29	.0112	.0925	.020	1.61	1.14	.94	.79	.71	.65	50.0	2.6
30	.0100	.1181	.018	1.34	.95	.78	.64	.60	.55	56.0	1.8

would be for one layer, and for any depth of winding we can find the permissible current by dividing I^2 for one layer by the number of layers and extracting the square root. These values have been calculated for all of the sizes of wire given in the tables and the carrying capacities may be read off for any depth of winding up to six layers.

As a general guide we may bear in mind that, as we multiply the number of layers by 4, 16, 64, 256, we each time halve the carrying capacity of the wire. From this we can see that the carrying capacity of the wires after a certain depth of winding has been considered decreases very slowly, though very fast with the first few layers. As we have already seen that we can vary different factors and that several of them are not accurately determinable, great accuracy in these calculations is not absolutely necessary.

If the wire we have found by the previous calculation does not give us sufficient carrying capacity we take the next larger wire or such a wire as will give us the desired current capacity and from this wire figure out the dimensions of a new armature. If we use the same number of wires of a larger diameter we shall, of course, obtain a greater cross section of armature. Thus it can readily be seen that in many cases unless we are very lucky, a number of calculations will be necessary before we obtain the proportions that suit us best.

In the foregoing calculation we have considered a smooth armature in which the whole circumference is available for winding. In connection with slotted armatures we have a large space occupied by the teeth that cannot be used for winding and therefore we must, instead of figuring on the whole circumference figure on that portion of it which forms the slots only. As a general rule, however, the attainable flux in a slotted armature is greater as the magnetic circuit is much better.

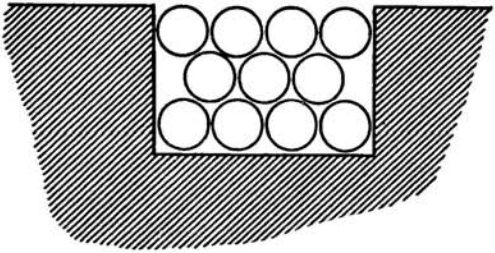


Figure 108.

In order to calculate the wire for a slotted armature we must figure on one slot by itself and the wire should be chosen if possible with reference as to how it will fill out the slot. Waste spaces, if any, can, of course, be filled out with insulation.

If the wires to be used are small they will very likely come to lie in the slots as shown in Figure 108 and if large as in Figure 109. For Figure 108 the approximate depth necessary for the slot can be found by multiplying the number of layers by .86 and this by the diameter of the wire. The width of the slot can be found by multiplying the diameter of the wire by the number of turns per layer.

After we have finally settled upon some size of wire we had best check up and see what the loss in pressure with this wire will be. To do this we first find from table I the resistance per foot of the wire in question and then measure the length in feet of the wire in one coil and multiply the resistance by the number of feet. If we have a bi-polar armature we again multiply this by half the number of coils (the two sides being in parallel). Since the loss in voltage is equal to the amperes multiplied by the resistance, we need but multiply the resistance so found by half the current to find the loss in voltage that will occur. This loss is of course

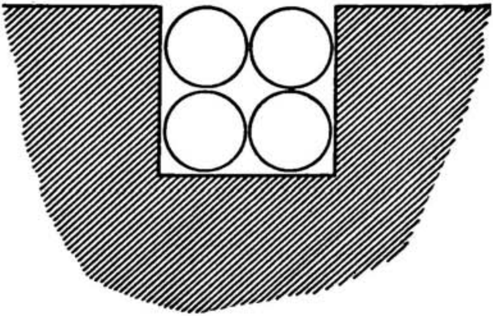


Figure 109.

in direct proportion to the current. It is not of much importance in armatures used for small currents or on constant current systems, but with heavy and variable current it is very important that it be kept as low as possible.

CHAPTER IX.

ALTERNATING CURRENTS.

An alternating current differs from a continuous current in that it is constantly changing, both in quantity and direction. It is customary to represent such currents graphically by means of curves such as are given in Figure 109a. That portion of the curve which rises above the base line is usually assumed to be positive and that below as negative. The current strength or the E. M. F. represented at any instant are equal to the height of a vertical line drawn from the base line to where it intersects the curve.

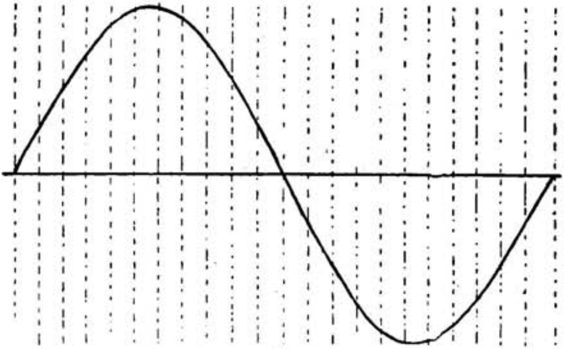


Figure 109a.

This continual change in strength and direction of the current gives rise to a very important phenomenon which is not very noticeable in connection with direct currents. This is the phenomenon of self induction. The term expresses the fact that an alternating current induces a counter E. M. F. in the very wires in which it circulates. This counter E. M. F, as the name implies, always opposes the impressed E. M. F. and is always in proportion to the rate of change of the current which causes it, that is, the more rapid these changes occur the greater is the self induction. This self induction is caused by the lines of force which spring up around a conductor in which a current of electricity flows, as illustrated in Figure 109b. These lines, in springing into existence, cut the wire from which they start in one direction and when they cease, as the current ceases, they cut the wire in the opposite direction. It is this cutting of the wire by the lines of force which produces the counter E. M. F. of self induction.

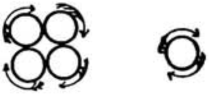


Figure 109b.

It is obvious that in the case of a single wire if this have a certain effect that, if we place a number of wires close together (as in winding an armature or magnet coil) the lines of force springing out from one wire will cut all of the wires of that coil and thus increase the effect. Thus, if we take as an example a coil of four turns, the current in one wire would have 4 times the effect as before, and if the same current flow around all of the wires this fourfold effect will again be multiplied

Figure 109c.

by 4, which will give us a self induction 16 times as great as that of a single turn. From this example we can see that the self induction is proportional to the square of the number of turns in a coil and that a coil to be used for alternating currents must not be made up of a great number of turns.

ALTERNATING CURRENT GENERATORS.

A typical alternating current generator as manufactured by the Westinghouse Co. is shown in Figure 109c.

Alternators are built with either the field or armature stationary or revolving. The Figure shows a machine in which the armature is stationary and the fields revolve. The fields in this case consist of 13 pairs of electro-magnets, the magnetic circuit of each pair being as illustrated in Figure 109d. These magnetic fields in sweeping along the inner surface of the wires cut them in a manner which has precisely the same effect as though the wires were being moved and the magnets held stationary, as is the case in direct current machines.

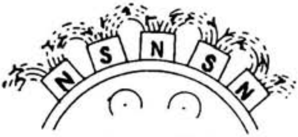


Figure 109d.

The fields, whether mounted upon the moving part or upon the stationary frame must be supplied by direct current and for this purpose a small direct current dynamo is usually supplied with alternators.

In the case of a revolving armature and stationary fields machine the windings shown in Figure 109c on the stationary element are placed upon the moving element and the electro magnets which make up the fields are placed upon the stationary element.

ALTERNATING CURRENT ARMATURES.

The simplest form of armature winding from which an alternating current can be obtained is shown in Figure 109e, where a single loop of wire revolves in a magnetic field produced by two pole pieces. During one complete revolution of the loop of wire a current is produced which flows in one direction during one half a revolution and in the opposite direction during the remainder of the revolution, or as indicated by the curve Figure 109a.

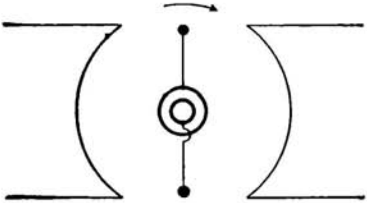


Figure 109e.

During one complete revolution or "cycle" the current alternates or reverses in direction twice. There are therefore in a given time twice as many alternations as cycles. If the loop of wire revolves at the rate of 60 revolutions per second a current would be produced which would pass through 60 cycles per second. This is equivalent to 120 alternations per second or 7,200 alternations per minute. Machines are generally rated at a certain number of cycles per second or alternations per minute, the former rating being more generally used.

It is evident that in order to generate a 60 cycle current the armature described above would have to revolve at the rate of 3,600 revolutions per minute. Such a speed would, obviously, be impractical. If the number of poles was increased to eight, or four pairs, one revolution of the loop of wire would produce a current which would pass through four cycles per revolution. A 60 cycle current could then be produced with a speed of 900 revolutions per minute.

While the simple loop of wire affords an easy method of explaining the action of the armature it is evident that an armature with a winding of this kind would be useless. The potential developed would be small and, assuming a field consisting of four pair of poles, most of the armature space would not be used. If, instead of the simple loop of wire, we should provide a system of wires as shown in Figure 109f we would still produce a current which would pass through four cycles per revolution, but, as we are cutting four times as many lines of force, four times the E. M. F. will be developed.

In Figure 109f the straight lines radiating from the center and marked by arrow heads indicate the conductors crossing the face of a drum armature, while the lines connecting the outer ends represent the connections at the rear of the armature and the lines connecting the inner ends those at the front of the armature. Two of the lines are carried direct to the two collector rings upon which the brushes bear. This form of winding is perfectly practical and is often used on machines generating a low voltage and heavy current.

Following out the changes which occur during a revolution of the armature it will be seen that, so far as the direction of current is concerned the action is similar to that described in the first case using the single loop

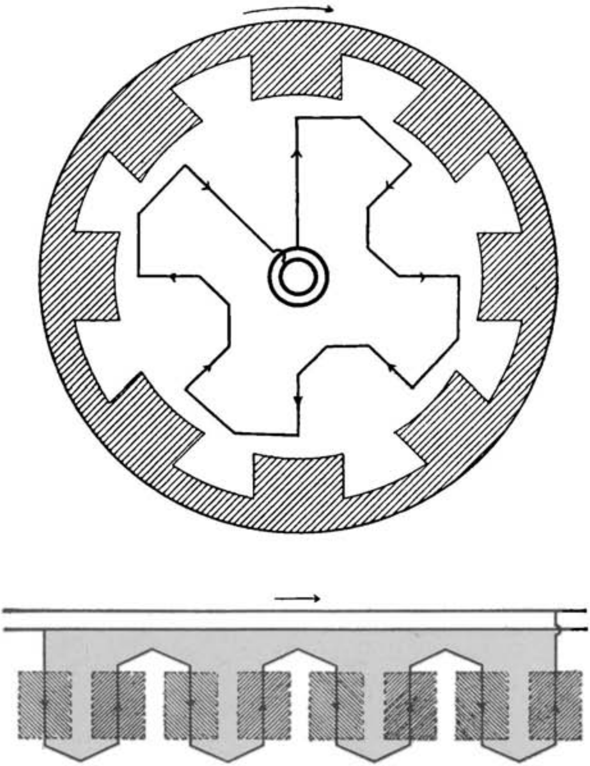


Figure 109f.

of wire except that here we have four pairs of poles. The number of poles can be increased to any number within practical limits but for an increase in the number of poles there must be a corresponding increase in the number of armature conductors.

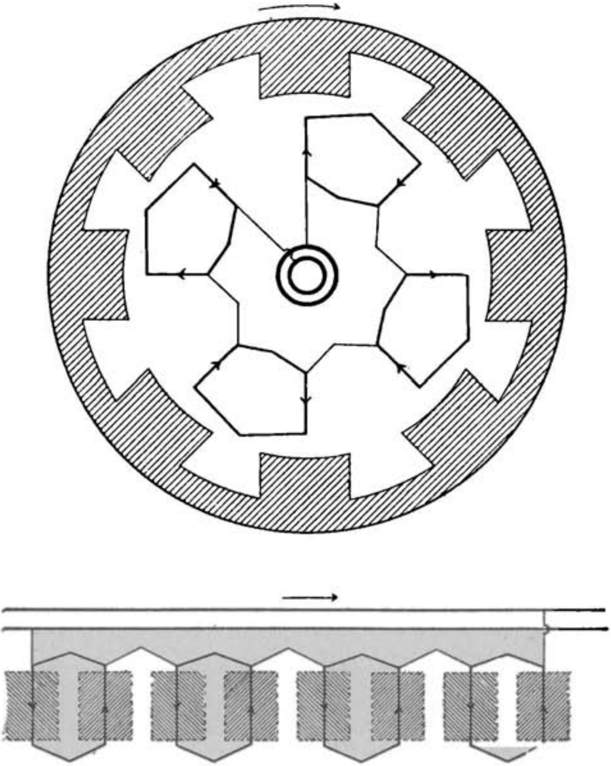


Figure 109g.

An increase in voltage may be obtained in several ways. The magnetic field may be increased. The speed of rotation may be made greater or the number of wires on the armature cutting through the field of force may be increased. The first of these means is limited by the design of the field. The second, the speed, is generally determined by the number of cycles to be produced. Therefore, as with direct current machines it is customary to increase the number of armature conductors for an increase in voltage.

The single conductor for each pair of poles shown in Figure 109f may be replaced by a number of conductors wound in the form of a coil (see page 129) and having the ends of each coil connected as shown in Figure 109g. An investigation of the changes occurring during a revolution will show that these occur uniformly in all conductors and a current will be produced which will vary in exactly the same manner as previously explained with the difference however that a considerably increased E. M. F. is now obtained.

This armature, even though wound with coils as described for Figure 109g, would still have considerable armature space unused, there being only one coil for each pair of poles. To take advantage of the unused spaces the method of winding shown in Figure 109h is employed. Here two coils for each pair of poles are spaced uniformly around the armature, there being eight poles and eight coils or, if in place of a coil separate conductors are used, there would be 16 conductors.

It will be noticed that the connection between the various coils do not occur regularly, only alternate coils being connected in the same manner. The reason for this will be made clear by reference to the simplified diagram Figure 109i, which represents two coils (or four

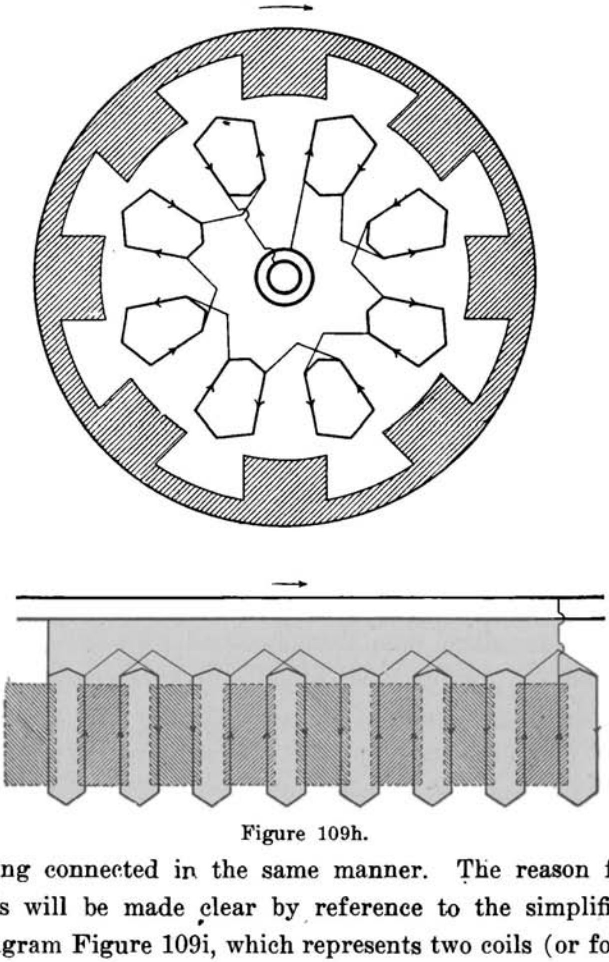


Figure 109h.

conductors) in a bi-polar field. The dotted lines represent the connections at the rear of the armature and the

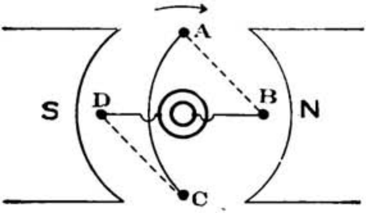


Figure 109i.

solid lines the connections at the front. The connections shown in the figure are identical with those shown in Figure 109h, but for one pair of poles.

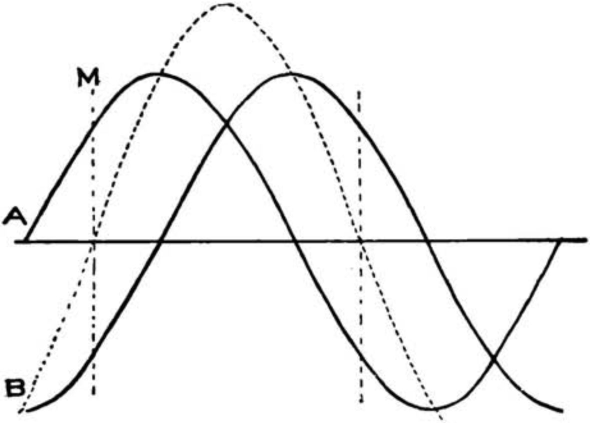


Figure 109j.

To ascertain the conditions with this connection refer to Figure 109j, where the variations in the induced E. M.

F. in conductors *A* and *B* are shown during one revolution. Similar changes will, of course, occur in conductors *C* and *D,* but for the sake of simplicity only two conductors are shown. The curve A represents the E. M. F's. in conductor *A* and the curve B those in *B*, but as these two conductors are connected together at the rear of the armature, E. M. F's. induced in the same direction will oppose each other and the curve is therefore shown 180° out of place. This may perhaps be better explained by illustration. When conductors A and B occupy similar positions with relation to the pole piece N, (i. e., cut lines in the same direction) A having arrived at a point just inside the tip of the pole piece and B is just about to leave the other tip of the pole piece positive E. M. F's. of equal amounts will be induced in both conductors, but as they are connected together at the rear of the armature, the resultant E. M. F. will be 0. This is shown at M, Figure 109 j. The curve shown by the dotted line represents the resultant E. M. F. during one revolution. It will be seen that the two conductors A and B oppose each other during part of the revolution and as a consequence of this the combined voltage is somewhat less than with an equal number of conductors placed one to a pole piece.

There are, however, important advantages gained by this form of winding, as in the lessening of armature reaction on loads, more convenience in winding and more radiating surface. This style of winding is extensively used.

The subdivision may be carried still further, and three or four sets of coils provided per pole piece, but the E. M. F. at the machine terminals will be still further decreased.

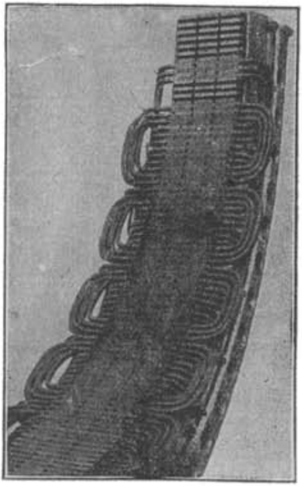


Figure 109k.

There are numerous methods of placing and connecting conductors on single-phase armatures. In the manufacture of machines for instance, it may be desirable to use the same form of armature for either single phase or two- or three-phase currents, and the windings are sometimes arranged so that this change may be made by simply using different connections for the same winding.

By reference to Figures 109k and 109l, we can get a clearer conception of alternators in which the armatures are stationary and the field revolves. Figure 109k shows part of stator of an Allis Chalmers generator. The winding used is diagrammatically laid out in Figure 109l.

The winding shown in Figure 109l is identical with that of Figure 109h, with the exception that it is spread out so as to cover the whole inner surface of the stator.

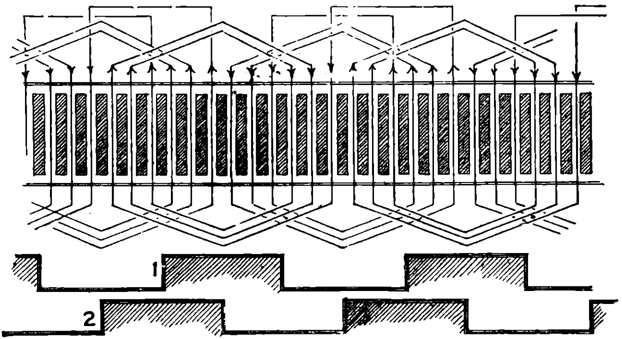


Figure 109l.

This has the double advantage of lessening the heating, because it provides greater radiating surface for the wires and also lessens the selfinduction of the armature.

This latter is an important item. The selfinduction acts as a counter E. M. F., which opposes the impressed E. M. F. It is proportional to the rate of change of the current strength and therefore varies with the frequency and the quantity of current used. In any given coil it is also proportional to the square of the number of turns of wire in that coil. If the 3 turns of which each coil in Figure 109l consists were all bunched into one, the inductance of that coil would be proportional to the square of 3, which is 9, while being separated as they are, it is equal only to the square of 1. In order to gain these advantages, it is, however, necessary to make some sacrifices in E. M. F.

In Figure 109l the shaded portions below the diagram represent the revolving pole pieces of the field. While these are in the position indicated at 1, no E. M. F. is being generated since an equal number of coils in the armature are opposing each other. When the fields assume the position shown at 2 the armature is generating at its maximum capacity. It can be seen from the above that a large part of the winding is practically dead during a great part of the time.

TWO-PHASE ARMATURES.

A two-phase or quarter phase winding with one conductor per pole, per phase, is shown in Figure 109m. It will be seen that this winding consists of two groups of conductors, each one of which is exactly similar to the single-phase winding shown in Figure 109f. Two entirely separate sets of conductors with their separate collector rings are provided.

The characteristics of the currents produced by this winding may be more easily understood from the simplified armature shown in Figure 109n. The currents produced in the armature are shown by the curves in Figure 109o, curve A representing the changes in the current in

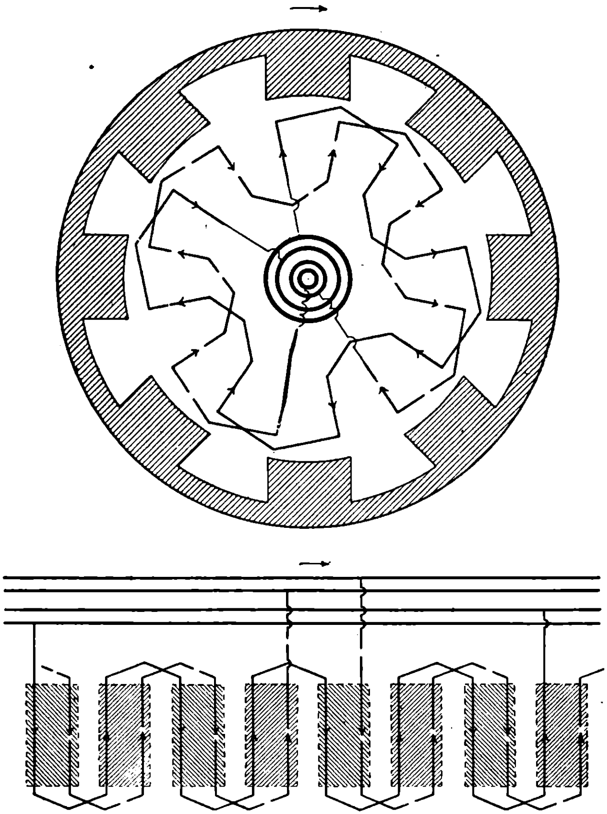


Figure 109m.

coil AA and curve B the current in coil BB. These two currents differ in phase by 90°.

In place of the single conductors, former coils may be used, each individual set of coils being connected as shown in Figure 109g.

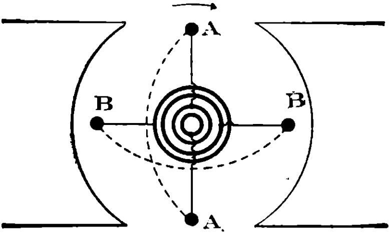


Figure 109n.

A two-phase winding, using two coils per phase, per pair of poles, is shown in Figure 109p. The coils are so arranged that when a slotted armature is used, adjacent sides of coils may be placed in the same slot.

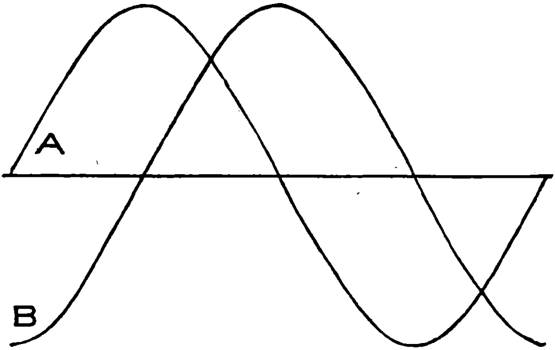


Figure 109o.

Two-phase armatures may be connected to three collector rings in place of the four shown in Figure 109p, one of the collector rings forming a common return for the two phases. The conditions may be represented by Figure 109q, where the lines OA and OB represent the

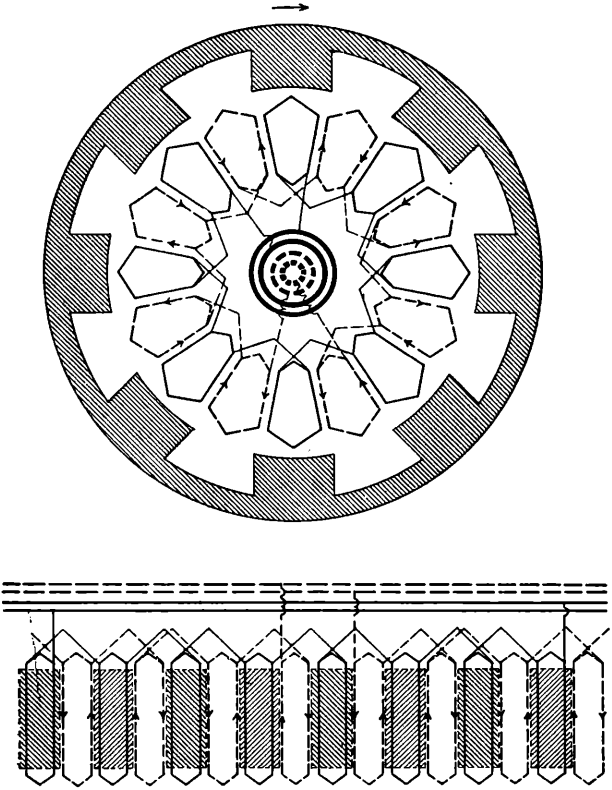


Figure 109p.

two armature phase conductors and the line from O the common return. The current on a balanced non-inductive load in the common return wire is equal to 1.4 times that in either phase wire. The E. M. F. between the phase wires A and B is equal to 1.4 times the E. M. F. in either phase.

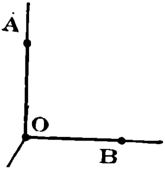


Figure 109q.

THREE-PHASE ARMATURES.

A three-phase armature winding is shown in Figure 109s. There are three conductors to each pole piece being spaced uniformly around the armature.

Figure 109t, which represents identical connections with Figure 109s, but is arranged for a bi-polar field, will give a better understanding of the relations of the currents in the three sets of conductors. In this figure three loops of wire form the armature conductors. Each conductor AA, BB and CC are connected diametrically across at the rear of the armature. One end of each loop is connected to a common wire, while the remaining ends are separately connected to three collector rings. If, instead of the common wire above referred to, six collector rings were used, each coil having its own terminals, a single-phase current could be obtained from each coil.

The curves Figure 109u represent the currents induced in the conductors during one revolution of the armature. Curve A represents the currents in coil AA, curve B that in coil BB and curve C that in CC. It

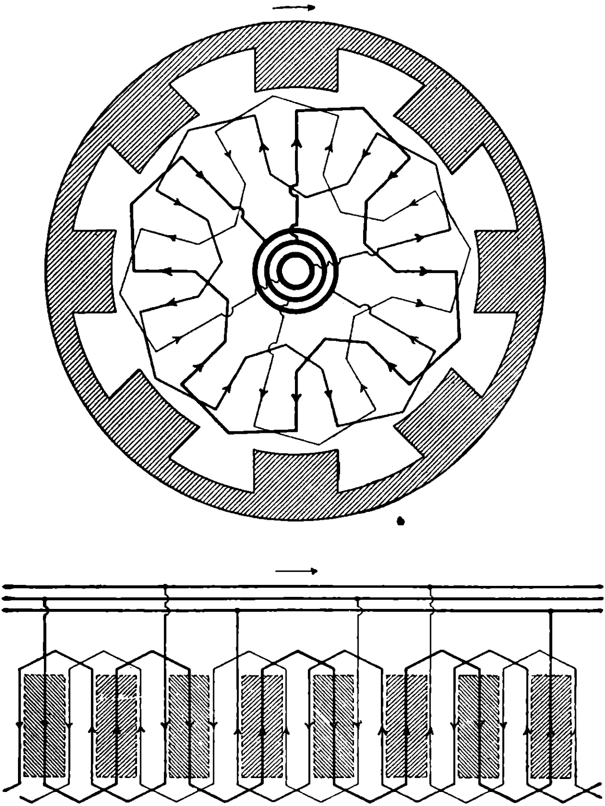


Figure 109s.

will be noted that conductor B, Figure 109t, occupies a position 120° behind conductor A, and conductor C occupies a position 120° behind conductor B and 240° behind conductor A. The currents in the conductors B and C will therefore attain a positive maximum 120° and 240° respectively, behind the current in conductor A or as indicated by the curves Figure 109u.

It will be seen by reference to the curves Figure 109u that at any point, the algebraic sum of the curves is 0.

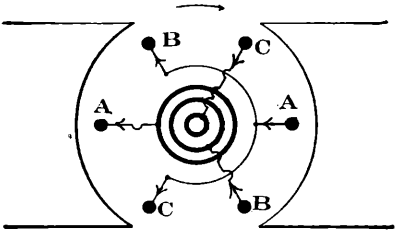


Figure 109t.

For instance, at point 2 current in B is at a positive maximum, while current in A and C is negative and of half the strength, their sum is therefore 0. Likewise at point 3 current in C is 0, while currents in A and B are opposite and of equal values, their sum also being 0. This is true of any point we may select on the curves. It is evident that by a proper connection of the conductors, one end of each may be brought to a common point. As the currents at this point always neutralize each other, it is unnecessary, at least theoretically, to carry a wire from this connection. In practice this fourth wire is often brought out, as the load connected to the machine may not be evenly balanced, as for instance, where lights are connected between the phases. It is also sometimes desirable to use single-phase motors connected between one of the phase wires and the common wire. This wire will only have to carry the unbalanced load.

The proper manner of connecting the armature may be readily determined from Figure 109t.

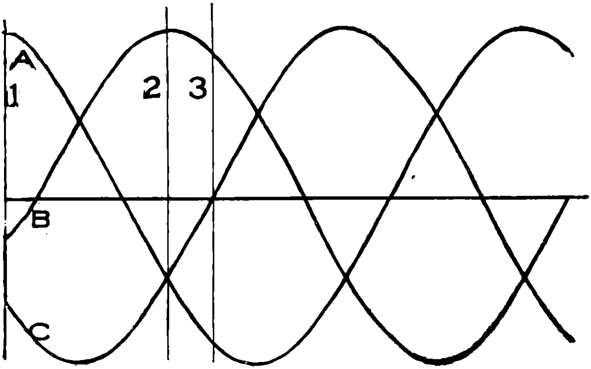


Figure 109u.

Considering the conductors as occupying the position as shown in Figure 109t, the currents in the conductors will then be as shown at Point 1, Figure 109u being a positive maximum in A and of half the strength and negative in direction in B and C.

It is evident that these three wires can be joined at a common point. Considering current flowing away from the center of the armature Figure 109t as positive, wire

A which occupies a position where the current is at a maximum strength in a positive direction can then be connected to wire B and C in which the current is negative (toward the center of the armature) and of only half strength, as shown by the position of these wires relative to the pole pieces.

This is known as the "star" or Y connection and is represented diagrammatically in Figure 109v. The voltage between any of the phases A, B or C and the common point M, is, of course, the voltage developed by one set of armature conductors. The voltage between any two of the phases as A and B, is equal to 1.73 times the voltage developed in any one set of armature conductors. As an example: If the voltage across A and M is 100, the voltage across AB, BC or CA will be 173. The watts output with a balanced, non-inductive load will be equal to 1.73 IE, where I is the current in any one of the phases, A, B or C and E, the voltage between any two phase wires, AB, BC or CA.

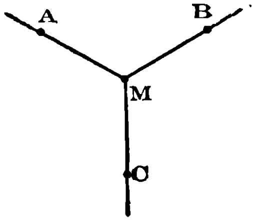


Figure 109v.

Figure 109w shows another method of connecting three-phase armatures. It is known as the "delta" or "mesh" connection and is represented diagrammatically in Figure 109x. The ends of each coil are connected to

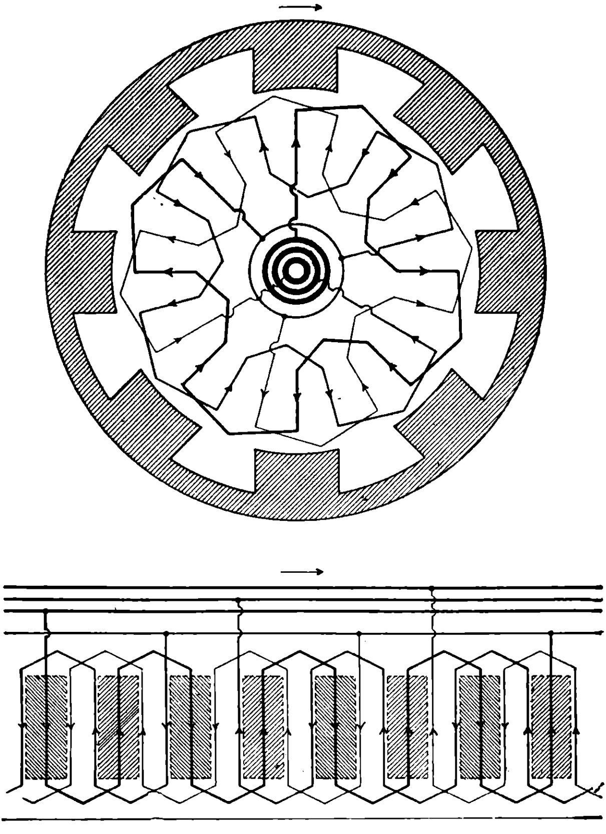


Figure 109w.

the ends of the others, these junction points being brought to collector rings. The voltage between phases is, in this case, the same as the voltage across any one set of armature conductors. The current, however, in any phase wire, is the resultant of the currents generated in the two sets of conductors connected to it and is equal to 1.73 times the current generated in any set of armature conductors. For instance, if 100 amperes was generated in one set of armature conductors as AB, the current in phase wire A would be 1.73 amperes. The watts output would be the same as in the previous case or 1.73 EI where E is the voltage between any two phases as AB, and I the current in any one of the phase wires beyond the point of their junction.

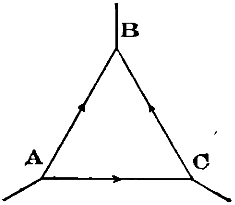


Figure 109x.

The method of joining the wires for a delta connection may be explained by means of the diagram, Figure 109x. The three lines A, B and C represent the three sets of conductors on the armature. Considering that line A represents conductor A, which occupies the position in the center of the pole pieces, it is evident that this conductor is generating its maximum current in a direction which is indicated by the arrowhead, **Figure 109x.** Each end of this coil may be connected to a

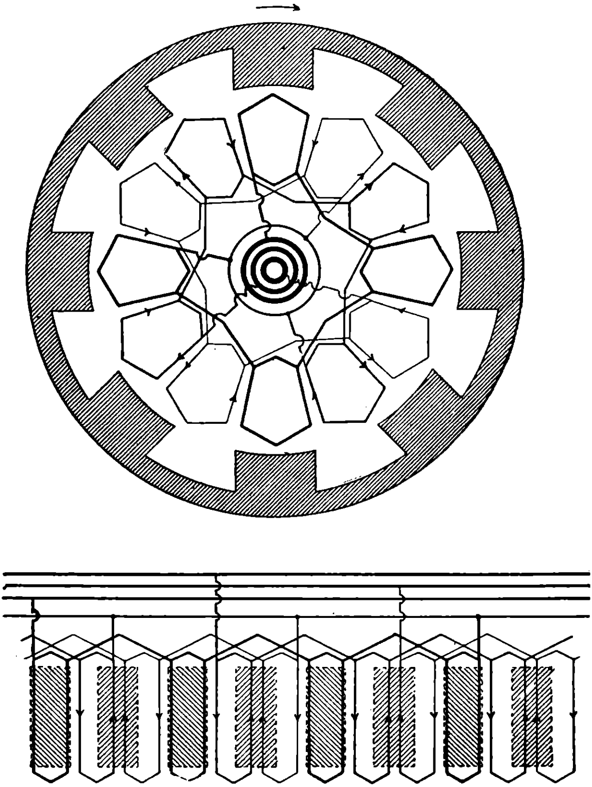


Figure 109y.

collector ring. The negative side of conductor B may now be connected to the same collector ring as the negative side of conductor A and the positive side of conductor C connected to the same collector ring as the positive side of conductor A. The remaining ends of conductor B and C are now connected to the remaining collector ring. This diagram may be compared with the armature connection shown in Figure 109w.

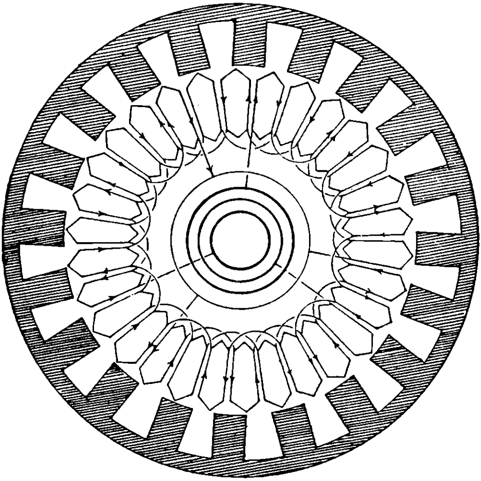


Figure 109ya.

A three-phase armature with coils instead of single conductors and one coil per phase for each pole piece is shown in Figure 109y. The armature shown is star connected, but may be connected delta by following the directions as described for Figure 109x.

A non-overlapping three-phase winding is shown in Figure 109ya. This winding is arranged for twenty poles and is a very useful one.

In Figure 109yb we have a three-phase winding with two coils per pole per phase. One part of any coil is always under the influence of two pole pieces. To avoid confusion in the drawing, the connections from coil to coil have been shown for one set of coils only. In the complete armature the other coils will connect to their collector rings and from coil to coil in the same manner as the coil shown complete.

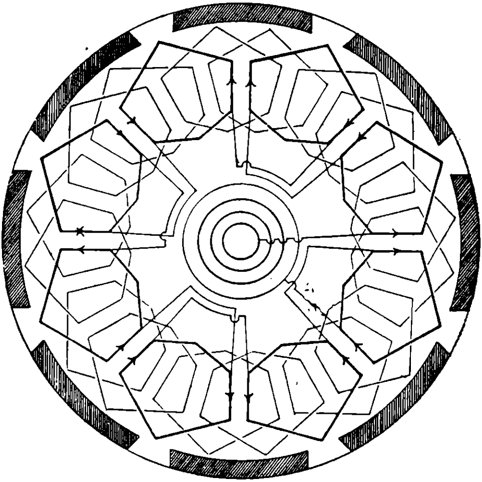


Figure 109yb.

Numerous other schemes of winding are employed for three-phase armatures. More than one coil per phase for each pole piece are sometimes provided and the armature conductors are not uniformly placed as regards the pole pieces, the object being to avoid dead centers where the winding is used for a motor armature.

While the term armature is generally applied to the revolving element of an electrical machine, in alternating current machines the armature is often made stationary and the fields arranged to revolve within it. The diagrams previously shown may be used for machines of this type by simply reversing the conditions shown, but in this case only one pair of collector rings will be used to convey the direct current to the revolving fields. The terminals of the three-phase windings on the stationary armature are simply brought to terminals mounted on the machine.

The squirrel cage armature is devoid of what could be termed a winding, being constructed of a number of copper bars embedded in the iron core of the armature, all the bars being connected together at each end of the armature by copper rings. The bars are insulated from the iron, but very little insulation is needed as the voltages existing are very low. An armature of this kind is shown in Figure 109z.

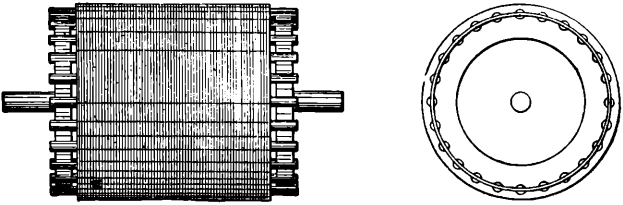


Figure 109z.

The squirrel cage armature has the disadvantage that it allows very heavy current to flow through the motor when it is started. To overcome this, the revolving element is provided with a winding arranged in the same manner as described for generator armatures. The connections for these windings differ however. They may either be wound in closed coils, one for each phase, or the ends of the separate coils may be brought to common junctions.

Figures 109za and 109zb are drawn to illustrate the winding of double-current machines or converters. If a machine of this type be driven through some external source, alternating currents may be taken off at the collector rings and direct current from the commutator. It may also be driven from the alternating-current side as a motor and caused to deliver direct current from the commutator, or may be driven from the direct-current side to deliver alternating currents.

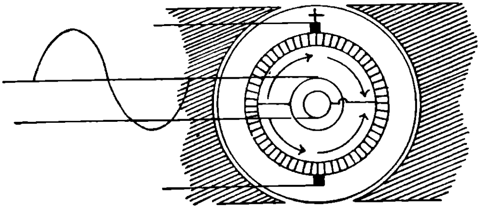


Figure 109za.

Figure 109za shows commutator and collector rings of a single-phase machine. Such machines are very seldom used, but will do to illustrate the principle. The position of the armature must be such that at the time of zero alternating voltage the taps connecting commutator and brushes are in the position shown, while when the alternating voltage reaches its maximum value they must be directly under the brushes bearing upon the commutator. We can thus see that at the moment the alternating E. M. F. is at its highest, it is in direct connection with the line. An alternating current in the direction indicated by the upper curve at the left will therefore pass in the same direction as the direct current in one part of the armature and tend to pass in the opposite direction in another part, as indicated by the inner arrows. The resultant current will depend upon whether the impressed E. M. F. is greater than that induced in the

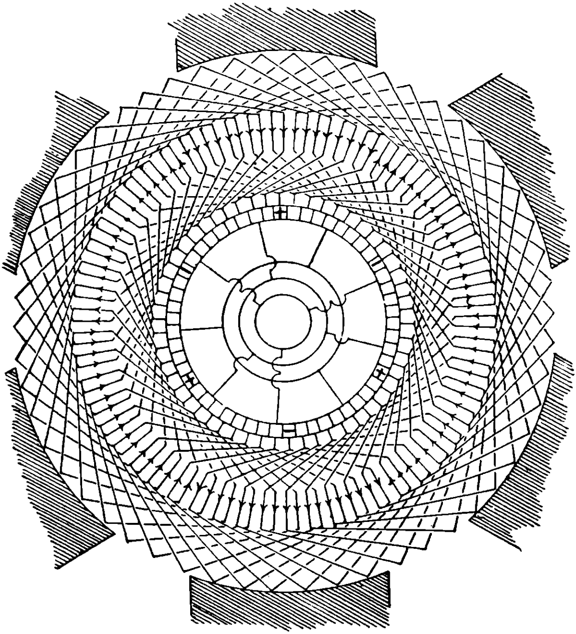


Figure 109zb.

coils subject to it or vice versa, and will thus be constantly varying in different parts of the armature. At the precise moment when the taps are under the brushes, for instance, the alternating current will oppose the direct current induced in both halves of the armature so that no current will be supplied by the converter, but whatever is used by the load will then come directly from the generator.

It is only the current from the generator in the direction opposed to that in which the converter current flows that tends to drive the converter as a motor. Whenever the current from the generator is in the same direction as that induced in the converter it has the same effect as the armature current and tends to oppose the motion. During the time that the alternating E. M. F. is at zero, the converter is receiving no current from the line generator and must, therefore, supply the load entirely by generated current; while at the time the alternating E. M. F. is at its maximum (if the armature is then in its proper position), it is then giving out no energy, but receiving some from the generator.

The converter usually has a very large commutator and collector rings ranging in number from two to twelve. Each collector ring must be connected to the armature at as many points as there are pairs of poles, and these connections must be evenly spaced on the armature.

Converter armatures may be arranged for 3, 6, or even 12-phase current. In such cases there must be one collector ring for each phase. A diagram of a three-ring converter armature is given in Figure 109zb.

STANDARD DIAGRAMS

The fully drawn out diagrams of armature windings are usually very difficult to follow because of the many overlapping and crossing lines representing the wires. In order to simplify matters as much as possible so-called standard or conventional diagrams are used. A number of such diagrams are shown in the following pages. In these diagrams the inner arcs, shown adjacent to arrows, each represent coils more or less as shown in Figure 109zc which represents a typical winding. By comparing these conventional diagrams with the above Figure and also with Figure 109 l (page 174), which shows a single-phase winding; as well as with the various schematic diagrams given they can be readily understood. The connections must be such that the re-

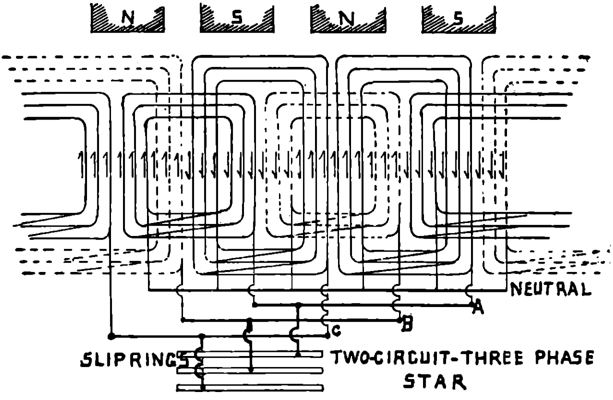
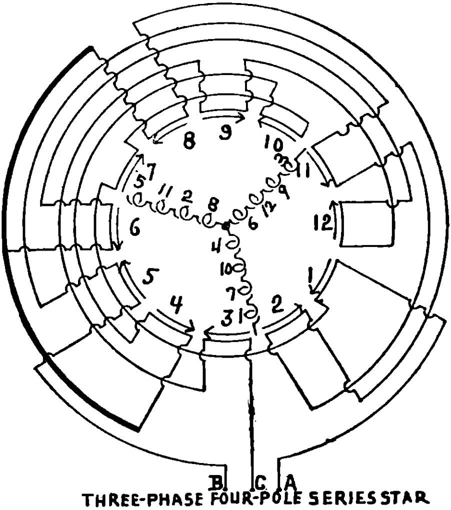


Figure 109zc.

sultant neighboring poles oppose one another as indicated by the arrows. Trace each circuit from its phase end.

MISCELLANEOUS

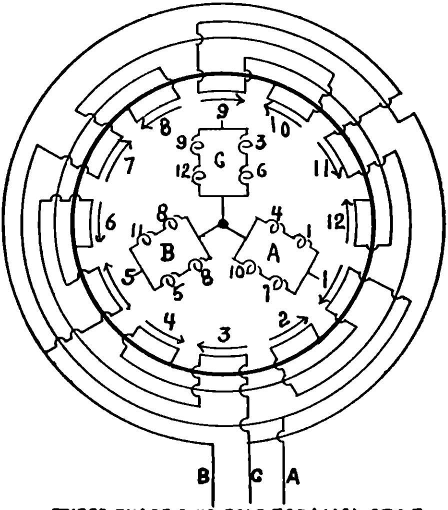
If two single-phase machines be coupled to make up a two-phase system their combined E. M. F.'s will be 1.41 times that of the single-phase voltage.



THREE-PHASE FOUR-POLE SERIES STAR
Figure 109zd.

If three such E. M. F.'s be coupled to make up a "star" connected three-phase system their combined voltage will be 1.73 times that of the original. In both cases, for the same amount of energy, we may therefore reduce the current correspondingly. A two-phase system will need only 0.71 times, and a three-phase system 0.58 times the current of a single-phase system.

A two-phase winding may be arranged with either four or three wires. But with three wires one will be common to both phases and will carry 1.41 times as much current as either of the other two.



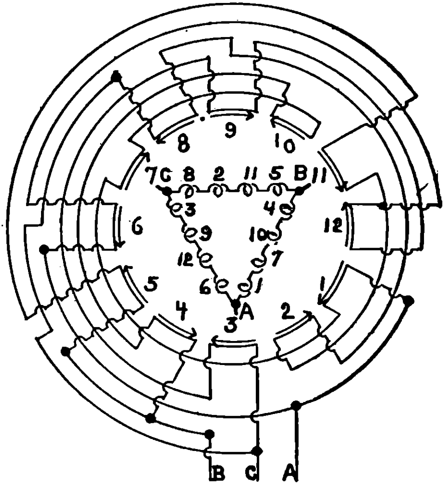
THREE-PHASE FOUR-POLE PARALLEL STAR

Figure 109ze.

If a "star" connected three-phase system be changed to the "delta" connection it will have the voltage of a single-phase only and will have to carry 1.73 times as much current as it did before to deliver the same energy.

Single-phase induction motors are not self starting. They must be either split-phase or of the repulsion type. A repulsion motor is reversed by shifting the brushes; a split-phase motor must have the connections of the auxiliary winding reversed.

A three-phase motor may be reversed by changing any two of its supply wires. To change the direction of rotation of a two-phase motor we must reverse one phase.



THREE-PHASE FOUR-POLE SERIES DELTA
Figure 109zf.

Any machine may be connected to a lower voltage with corresponding loss of power and efficiency but no machine should be subjected to a higher voltage without very careful examination and testing. If motors are to be fitted for a different voltage the arrangements should be such that the voltage per coil always remains the same. Two coils designed for 220 volts, for instance, may be connected in series for 440.

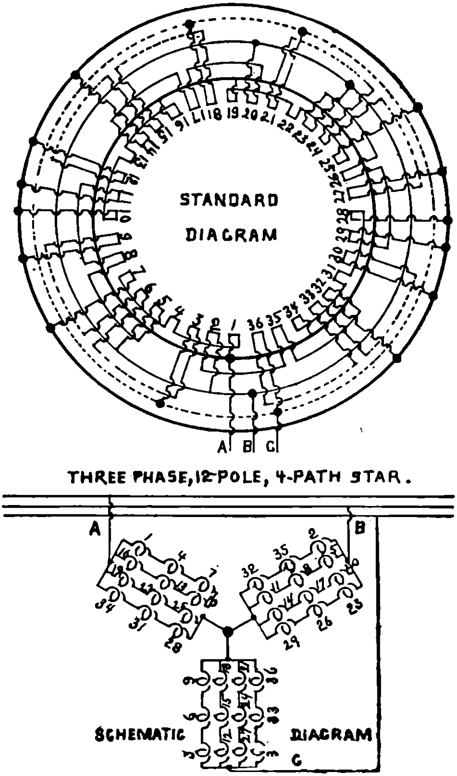


Figure 109zg.

In three-phase installations the connections may be changed from "star" to "delta" to reduce voltage but there should be no increase in current. If the motor was "delta" connected it may be changed to "star" for a higher voltage.

Two-phase systems are practically obsolete. But there are still some two-phase motors which it may be desirable to connect to three-phase systems. The simplest manner of doing this is by means of standard transformers connected as shown in Figure 109zh. One transformer must have an 86.6 per cent tap and the middle connection of the other transformer is used.

The self induction of a coil connected to an alternating current circuit increases as the square of the number of turns and is one of the means of keeping the current in check. If we lessen the number of turns we increase current flow and vice versa. If we change the frequency to a higher one we also lessen the current flow: lowering it increases the current. Voltage and frequency should vary together. The heating in pole pieces also increases with the magnetic flux and this must be watched. As a rule the current carrying capacity of a motor increases with speed, because of better ventilation.

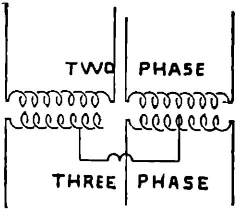


Figure 109zh.

CHAPTER X.

MAGNET WINDING.

Calculation of Electro-Magnets.

Magnetism is now conceived to exist in the form of a flow or flux which behaves very much like the flow of electric current. The law of the magnetic circuit is very similar to Ohms law.

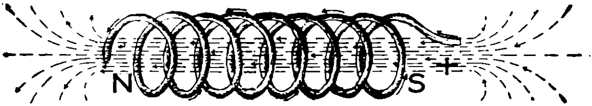
$$\text{It is } \frac{\text{Magneto Motive Force}}{\text{Reluctance}} = \text{Magnetic Flux.}$$

Magneto Motive Force means to magnetism what Electro Motive Force means to current flow. Reluctance is also of the same nature and influence as resistance in the electric circuit. Furthermore, the law of reluctance is the same as that of electrical resistance; it increases directly as the length and inversely as the cross section. The above formula can, of course, also be transposed in the same well known way as Ohms law, thus:

Magneto Motive Force = Flux × Reluctance, and

$$\frac{\text{Magneto Motive Force}}{\text{Flux}} = \text{Reluctance.}$$

The strength of the magnetic field is expressed by the number of lines of force per unit of area. These lines are assumed to flow along the iron or air inside of a helix at right angles to the current circulating around the space inclosed in the wires, as shown in the figure. They leave the coil at the north pole and re-enter it at the south pole and the relation in regard to direction of current flow and direction of magnetism is always as shown in the figure. A reversal of the direction of current will bring with it a reversal of the direction of the lines of force or polarity of the helix.



The fundamental relation of the quantity of current flow and the resultant magnetism is the following: A unit pole exists at the end of an infinitely long column of air of a cross section of one square centimeter which is provided with an exciting force of one absolute electromagnetic unit of current strength per centimeter in length. The absolute unit of current strength is equal to ten practical units or amperes and the exciting current in the above case is therefore equal to ten amperes. From such a pole one line of force per square centimeter of surface is supposed to emanate in all directions as from the surface of a sphere. The surface of a sphere of one centimeter radius, it can be shown, is equal to $4 \times \pi$ (or 3.14), which equals 12.56. As we, however, do not usually deal with the metric system, it will be convenient to translate these quantities into square inch measurements. We have already seen that the reluctance of the magnetic circuit decreases as the cross section of the air or iron inside of the helix increases and therefore, the flux per square inch must be greater than per square centimeter. If we, therefore, increase the diameter of our helix so that it shall have a cross section of one square inch we shall thereby correspondingly increase the number of lines. One inch is equal to 2.54 centimeters, therefore a surface one inch square will give us 2.54 × 2.54 as many lines as a surface one centimeter square. But as we increase the area to get square inch measurements we must also increase the length, as this again increases the reluctance 2.54 times we have as a net result the flux from a given exciting force per inch 2.54 times as great as from the same exciting force per centimeter.

We have already seen that the flux from a column of one centimeter cross section and one absolute unit of current strength is 12.56 and as the practical unit or ampere is but 1-10th of this, the flux per ampere turn per square centimeter is but 1.256. In order to find the number of lines that will be produced in air by one ampere turn per square inch we therefore multiply 1.256 by 2.54 which gives us 3.19, which is the number of lines of force created in air by one ampere turn (one ampere circulating once around a coil) in air; the cross section of the column of air being one square inch and there being one turn for every inch in length. If we increase the diameter of the coil the flow will be correspondingly increased; if we decrease it the flow will be decreased; also if we increase the exciting force the flow will be increased and vice versa.

INFLUENCE OF IRON.

If we now insert a piece of iron into the helix we shall find upon investigation that the flow is enormously increased. The increase caused in this way varies with the quality of the iron and also with the degree of magnetization to which the iron is subject. If to any piece of iron we apply a steadily increasing magnetizing force we shall at first find the magnetism steadily increasing in about the same proportion as the exciting force but after a certain point is reached (varying somewhat with the kind of iron) further magnetization becomes more and more difficult until at last the further increase is no greater than it would be with air. At this point the iron is said to be fully saturated. The various curves in Figure 16 represent these changes in the iron graphically and a study of them will help to familiarize us with this fact.

For whatever purposes an electro-magnet may be used we may always consider it as requiring a certain number of lines of force.

The condition of saturation to a certain degree; of being capable of lifting a certain number of pounds; of causing a certain induction when used for spark coils or transformers or of causing a retardation or lag of the current behind the electro-motive force may all be expressed in this way.

The first part of the problem in determining the proportions of an electro-magnet, is to find the size of the iron core that had best be used to accommodate the rerequired number of lines of force. For this purpose it is most convenient to consult Table III. This table gives, in the first column to the left, the densities attainable with good wrought iron and at the right the same for ordinary cast iron. The data from which this table is figured are taken from Wiener's great work "Dynamo Electric Machines" and represent average values of many samples of iron tested. In this table we give only the best and the poorest iron used for this purpose. There are several special kinds of iron, but the data regarding these had best be obtained from the manufacturers. If very accurate results are aimed at the samples of iron to be used must be tested. If the figures given in the table are to be used as the basis of the calculations without special knowledge as to the quality of the iron at hand liberal allowances for possible variations should be made.

The table gives in the first column of each half of the page, the number of lines that can be obtained per

TABLE III.

Annealed Wrought Iron	Permeability μ	Ampere Turns	Lines in Air	Air Gap	Traction	Ordinary Cast Iron	Permeability μ	Ampere Turns	Lines in Air	Air Gap	Traction
125000	43.5	900.	2871	.68	216.	72500	32	700.	2233	.5	72.8
122500	47.5	800.	2552	.74	208.	70000	38	570.	1818	.6	67.9
120000	53.3	700.	2233	.83	199.	67500	45	470.	1499	.7	63.1
117500	61.4	600.	1914	.96	191.	65000	50	400.	1276	.78	58.5
115000	78	500.	1595	1.2	183.	62500	58	340.	1084	.91	54.1
112500	89	395.	1260	1.4	175.	60000	64	295.	941	1.0	49.9
110000	119	290.	925	1.8	168.	57500	70	257.	819	1.1	45.7
107500	177	190.	606	2.7	160.	55000	78	222.	708	1.2	41.9
105000	240	137.	437	3.7	153.	52500	87	189.	603	1.3	38.2
102500	298	108.	344	4.7	146.	50000	98	160.	510	1.5	34.6
100000	345	91.	290	5.4	138.	47500	109	136.	434	1.7	31.2
90000	548	50.7	162	8.5	112.	45000	121	116.	370	1.9	28.1
85000	669	39.7	127	10.4	100.	42500	132	101.	322	2.1	24.9
80000	800	31.2	100	12.5	88.7	40000	143	88.	280	2.2	22.2
75000	949	24.7	79	14.8	78.0	37500	155	76.	242	2.4	19.5
70000	1111	19.6	63	17.4	67.9	35000	169	65.	207	2.6	20.0
65000	1300	15.7	50	20.3	58.5	32500	178	57.	182	2.8	14.5
60000	1449	13.0	41.4	22.6	49.9	30000	189	50.	159	3.0	12.5
55000	1553	11.1	35.4	24.2	41.9	27500	196	44.	140	3.1	10.4
50000	1634	9.6	30.6	25.5	34.6	25000	201	39.	124	3.1	8.7
45000	1660	8.5	27.1	25.9	28.1	22500	204	34.5	110	3.2	7.1
40000	1673	7.5	23.9	26.1	22.2	20000	206	30.5	97.2	3.2	5.5
35000	1691	6.5	20.7	26.4	20.0	17500	202	27.1	81.4	3.1	4.2
30000	1714	5.5	17.5	26.8	12.5	15000	195	24.1	76.9	3.0	3.1
25000	1748	4.5	14.3	27.3	8.7	12500	183	21.3	68.0	2.9	2.0
20000	1786	3.5	11.2	28.0	5.5	10000	169	18.5	59.0	2.6	1.4
15000	1744	2.7	8.6	27.3	3.1	7500	147	16.0	51.0	2.3	.78
10000	1428	2.2	7.0	22.3	1.4	5000	124	13.0	41.5	1.9	.34
5000	909	1.7	5.5	14.2	.34	2500	87	9.0	28.7	1.4	.085

square inch; in the second column the permeability or multiplying power of the iron (usually designated by the Greek letter μ) at that particular density; in the third column we have the number of ampere turns per inch length of core, required to produce the corresponding density; in the fourth column the lines produced in air without the help of the iron and in the fifth column the influence of the air gap is made clear. In the last column, finally, we give the traction or pull in pounds obtained with the given density per square inch.

In order to produce a certain number of lines we may select the quantity of the iron to be used and the exciting force required from a wide range of possibilities. In all cases the number of lines from a given exciting force or number of ampere turns will depend upon the cross section of the iron, so that in order to get the total number of lines it is necessary to multiply the area by the density and the ampere turns given in the table will be sufficient to produce this number.

It may be noted in passing that much greater densities and much stronger lifting powers have been developed in laboratories. Ewing in some of his experiments carried the magnetization so far that his magnet became capable of lifting 1,000 pounds per square inch of surface.

By an inspection of the table it will be noted that the permeability is a very variable quantity. It represents the number of times that the flow of lines in iron is greater than the flow in air. At the highest density given, when the iron is nearly saturated, we see that it is only 43.5 while at a density of 20,000 it is as high as 1786. This means that at the lower density we get about 41 times as many lines from the same exciting force as we do at the higher.

In each column the figures given under "Air Gap" are intended to facilitate the calculations of the number of ampere turns necessary to force the corresponding flux through the air gap in the magnetic circuit. The figures given show how many times greater must be the exciting force for each 1-64th of an inch of air than is required for 1 inch of iron at the densities given in the various horizontal rows in the table.

To find the number of ampere turns required for any air gap we first find, for the density desired, the number of ampere turns per inch required for the kind of iron of which the pieces adjacent to the gap are made. Multiply this by the figures given under "Air Gap" and by the number of 64ths of an inch which represents the length of the air gap. It is, of course, understood that the air gap is of the same cross section as the pole pieces from which it is figured. If two cores are unusually expanded or contracted at the points where the lines of force pass between them this fact must be taken into account and the total number of ampere turns correspondingly increased or decreased.

In order to more fully grasp the meaning of the table let us assume the following example: Suppose we wish to magnetize a piece of iron to a density of 100,000 lines per square inch. We see from the table that this requires 91 ampere turns but this figure is based on the assumption that there are 91 turns to every inch in length of the whole magnetic circuit. In order to fulfill this condition the iron must be in the shape of a ring or closed loop which may be of any shape or size so long as it has the required number of turns per inch. It is not necessary that these turns be evenly distributed; if only a part of the space is available for winding we must crowd the requisite number of turns into that space. Now since the multiplying power of the iron at the density of 100,000 lines is 345 it follows that if we cut away 1 inch of the iron we shall require 345 times as many turns for that inch as would be required if the iron were to remain. The total number of turns will therefore be 345 × 91 for the air gap of 1 inch in length and 91 for each inch in length of the iron core. If the air gap is only 1-4th or 16-64ths of an inch we shall need $16 \times 5.4 = 86.4 \times 91$ for that quarter of an inch.

From a study of the table we can see that an addition of an inch or two to the length of the iron, in order to obtain room for the winding, will not affect the problem very much if the air gap is relatively large, while on the other hand it will be very important if the air gap is very small or entirely absent.

MAGNET WINDING CALCULATIONS.

In the following winding tables there is given, in connection with each wire considered, the resistance of that wire of a length of one turn wound upon a spool of 1 inch in diameter, as well as the radiating surface of the same length of wire and the number of turns per linear inch of that wire.

If we subject one such a turn to a certain E. M. F. we shall obtain a certain current which will be numerically equal to the E. M. F. divided by the resistance given. As this current circulates but once around the coil it will also be numerically equal to the ampere turns. If we add another turn of wire to the same cross section upon the same spool, we shall, from the same E. M. F. obtain only half as much current; but as this current circulates twice around the coil we shall have exactly the same number of ampere turns as before. No matter how far we may extend this process, so long as we do not change the length of the turns or change the voltage, we cannot change the number of ampere turns. We can see therefore that in order to obtain a certain number of ampere turns upon a given spool we must use a certain size of wire.

As the length of a turn and consequently its resistance increases directly as the diameter of the spool it is evident that the greater the diameter of the spool, the lower must be the resistance of the wire per foot, in order to give us the same number of ampere turns. We can also see from the above that the amount of energy required to produce a given number of ampere turns is not at all a fixed quantity and the greater the number of turns of wire we use the lower will be the expenditure of energy to produce the required magnetism. On the other hand also, the fewer turns we provide the lower will be the first cost of construction. We may therefore choose from a wide range of possibilities the winding which seems to be best suited to our needs.

As it is also a well known fact that the heating effect of an electric current is proportional to the square of the current and as the current grows smaller and smaller with each additional turn while the ampere turns remain unchanged, it follows that we may get a certain number of ampere turns with about any degree of temperature rise of the coil we may desire.

We have therefore the general rule: The size of the wire (i. e. cross section) determines the magnetizing effect, and the greater the cross section of the wire the greater the magnetizing effect, other factors remaining unchanged.

And also: The number of turns of wire we wind upon a coil determines the temperature rise of that coil and the efficiency; and the greater the number of turns the lower will be the heating and the higher the efficiency of the winding. We must not, however, apply this indiscriminately to all coils. It is true only as long as the length of the turns does not change as, for instance, where we are considering a change in length of the spool only. In most coils there are a number of layers wound over one another; in such a case each succeeding layer is longer than the one below it and consequently has a higher resistance. This brings with it

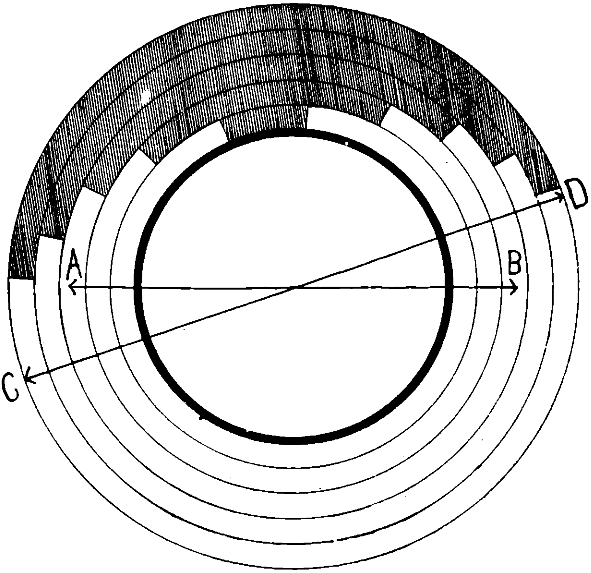


Figure 110.

a consequent decrease in the number of ampere turns. In order therefore to get the true values for a coil several layers deep we must use the mean diameter of all the layers. This consideration is more important with small spools where the diameter of the wire is large than with larger spools and small wire. This is well illustrated in Figure 110. In this figure the unshaded portions of the various circles are all of the same length and the shaded portions represent graphically the gradual increase of resistance of the outer layers over that of the inner. This figure can also be used, as we shall see later, to illustrate the changing proportions of resistance and radiating surface of coils.

Since $\frac{E}{R}$ = a.t., or ampere turns, $\frac{E}{a.t.} = R$; R, being the resistance as given in the table and a. t. the ampere turns. Since further resistance increases directly as the diameter of the spool and the mean diameter of the winding we may rewrite the formula thus:

$R = \frac{E}{a.t. \times D}$; R being the resistance of a turn of wire as given in the table and D being the diameter of the coil taken at half the depth of winding, as from A to B in Figure 110. This gives us the mean length of all the turns of wire placed upon the coil. Therefore, in order to find directly the resistance of a wire to be used in order to give a certain number of ampere turns with a given voltage and a given spool, we assume some depth of winding and find from this the mean diameter of all the turns. Next we multiply the ampere turns by this and divide the E. M. F. by this product as in the formula above. The result will be the

TABLE IV.

B. & S.	Single silk		Double silk		Dble. cotton		Resistance	I^2 3 sq. in. per watt. Cool	I^2 2 sq. in. per watt. Warm	I^2 1 sq. in. per watt. Hot
	Turns per inch	Radiating Surface	Turns per inch	Radiating Surface	Turns per inch	Radiating Surface				
40	193	.016	143	.022	90	.035	.273	.027	.04	.08
39	181	.017	133	.024	87	.047	.216	.036	.055	.11
38	169	.018	126	.025	84	.037	.172	.046	.07	.14
37	156	.020	119	.026	81	.039	.136	.070	.10	.20
36	143	.022	111	.028	77	.041	.108	.086	.13	.26
35	131	.024	104	.030	73	.043	.075	.13	.20	.40
34	120	.026	97	.032	69	.045	.068	.15	.23	.46
33	111	.028	91	.035	66	.047	.054	.22	.32	.64
32	101	.031	83	.038	63	.050	.043	.29	.44	.88
31	91	.034	77	.041	59	.053	.034	.37	.56	1.12
30	83	.038	71	.044	55	.056	.027	.54	.81	1.62
29	76	.041	67	.047	53	.059	.022	.72	1.07	2.14
28	68	.046	60	.052	48	.065	.017	1.0	1.5	3.00
27	63	.050	55	.056	45	.069	.014	1.3	2.0	4.00
26	56	.055	50	.062	41	.075	.011	1.9	2.8	5.60
25	50	.062	46	.069	38	.081	.0084	2.7	4.1	8.2
24	45	.069	42	.075	35	.088	.0070	3.5	5.3	10.6
23	41	.077	37	.083	32	.095	.0053	5.2	7.8	15.6
22	36	.086	34	.092	30	.104	.0042	7.3	11.0	22.
21	33	.094	31	.101	28	.113	.0034	10.	15.0	30.
20	29	.106	27	.113	25	.126	.0026	14.	21.	42.
19	26	.119	25	.126	22	.138	.0021	20.	30.	60.
18	24	.132	22	.138	21	.151	.0017	27.	40.	80.
17	21	.148	20	.154	19	.166	.0013	39.	59.	118.
16	19	.166	18	.173	17	.185	.0011	52.	78.	156.
15			16	.191	15	.204	.00083	70.	105.	210.
14			15	.213	14	.226	.00066	107.	161.	322.
13			13	.238	12	.251	.00053	149.	224.	448.
12			12	.267	11	.279	.00042	217.	325.	650.
11			11	.298	10	.311	.00033	301.	451.	902.
10			9.5	.329	9.1	.342	.00026	421.	632.	1264.
9			8.4	.370	8.1	.383	.00021	587.	880.	1760.
8			7.5	.414	7.3	.428	.00016	842.	1262.	2524.
7			6.9	.455	6.8	.468	.00013	1167.	1750.	3500.
6			6.0	.521	5.8	.534	.00010	1680.	2521.	5042.

resistance of a wire 3.14 inches long that would give us exactly the number of ampere turns sought for. By selecting the nearest resistance to this from the table it will indicate the nearest size of wire which, wound to the depth we have assumed at the start, would give us the required number of ampere turns. As it is very unlikely that we shall strike exactly any number given in the table we may select the one nearest to it either higher or lower as the case may seem to warrant.

Example: What is the smallest wire that will give us 11,800 ampere turns upon a core 9 inches in diameter, voltage 110? Let us assume a depth of winding of one inch which gives us a mean diameter of ten inches. Next we divide 110 by 10 × 11,800, which gives us .00093; this is the resistance we must have in one turn of wire to give us 11,800 ampere turns. Tracing along in Table IV. under "Resistance" we come to .00083, which corresponds to a No. 15 wire. This resistance is a little lower than we were looking for and we may now check back and see what this wire will do for us. In order to find exactly how many ampere turns this wire will give us we divide 110 by 10 ×.00083 (the resistance of an average turn on a 9 inch core), which gives us 13,253. As this is more than we care for, we try the next smaller wire, which has a resistance of .0011; dividing 110 by 10 × .0011 gives us 10,000. We may now choose either of these wires as we think best. If we desire to have exactly the right number of ampere turns we can either increase or decrease the depth of winding until it comes out just right for one or the other of the two wires.

Having thus found the proper size of wire to use, our next consideration is to find how many turns must be placed upon the spool to bring the heating within the proper limits. For general purposes it is customary to allow about 2 sq. inches of radiating surface for each watt used in the coils. The value of the radiating surface may, however, differ considerably from this. In connection with armatures it is often taken as low as 1 and this value may also often be used in connection with magnets that are in circuit only for a very short interval at a time. The more radiating surface there is allowed per watt the more expensive becomes the winding, hence it is usual to make this as low as practicable.

The watts in any electric circuit are equal to the E. M. F. squared and divided by the resistance. For the condition stated above (2 inches of surface for each watt) we must therefore arrange the coil so that $\frac{E^2}{R}$ may not be greater than $\frac{r.s.}{2}$; r.s. being the radiating surface. We may make r.s. as much greater than $\frac{E^2}{R}$ as we choose without doing any further harm than that we shall be using more material than economy of construction demands. For general purposes, however, we shall strive to make them equal.

To get the equation into practical form for our purpose we transpose it and find that $E^2 \times 2$ must equal r.s. × R. $E^2 \times 2$ is easily found. The value of r.s. and R can be taken from the table, which gives them in direct reading for a 1 inch spool. In the table there is but one value for resistance given and that is for a coil running quite cool. There are 3 values of r.s. for different thicknesses of insulation given. The double silk is the same generally as the single cotton and can be used for both. To find the resistance of a coil of any diameter and depth of winding, multiply the resistance given in the table by the mean diameter of the winding as A to B Figure 110. To find the radiating surface of the same coil multiply the diameter of the wire by the total diameter of the coil as from C to D in the figure. This is all we need to figure to begin with, because the radiating surface and resistance increase in the same ratio directly as the length, and as long as we do not change the proportion of the first section considered they will remain the same throughout any length of spool. If, however, we attempt to consider a different depth of winding we must again determine the resistance and the radiating surface, since we can see from the figure that the proportions of the two are constantly changing.

In the calculations of radiating surface we must neglect the ends. In general practice the length of the spool is made much greater than the depth of winding and as the ends therefore have very little effect upon the center they must be neglected entirely for it is the heating of the center that limits the watts to be used. If, as may in exceptional cases occur, the depth of winding is equal to the length of spool the radiating surface of the ends may be reckoned with.

In order to find what the resistance would have to be if we were to wind only this one section we divide $E^2 \times 2$ by the r.s. for the diameter we have just found. This will give us a resistance much greater than we have in those few turns and we must add more such sections until the product of r.s. × R becomes equal to $E^2 \times 2$. In order not to affect the ampere turns we must leave the mean diameter as we had it in the first place and consider only a lengthening of the winding space. As we lengthen the coil we also increase the radiating surface in the same ratio as we increase the resistance. We therefore increase the product of the two as the square of the length of the coil or the number of sections used. That is, the product of the radiating surface and the resistance for two such sections as we have been considering would be four times and for 3 nine times that of one.

Since the product of r.s. × R increases as the square of the length, in order to find the length of winding necessary, we extract the square root of $\frac{E^2 \times 2}{\text{r.s.}}$ which gives us directly the number of turns of wire in each layer of the coil. Since the table gives also the number of turns per inch we can from this get the length in inches of the winding space necessary to accommodate them. From the mean diameter of the winding we have assumed we can now determine the number of layers and thus the product of the two will give us the number of convolutions to be placed upon the spool. As most winding is done by machines which at the same time count the number of turns, this is in precisely the shape in which it is to be used.

As an example let us assume that we have a case in which it is decided that a number 20 wire will give us sufficient magnetizing force and we are now to find how much space we shall have to occupy so as to obtain sufficient radiating surface. The voltage to be used is 110 and the diameter of the spool 9 inches; $110^2 \times 2$ equals 24,200 and the product of $R \times$ r.s. should be equal to this. A number 20 wire, double cotton covered, will give us exactly 25 layers or turns per inch. As we have a spool of 9 inches in diameter and assume a depth of winding of 1 inch we shall have a mean diameter of the winding of $9+1$ inches; the resistance of the 25 layers will therefore be $10 \times 25 \times .0026$, the latter number being the resistance taken from the table. This gives us .66 as the resistance of a winding of the mean diameter of 10 inches and a width equal to the diameter of the wire which, we may say, forms one section of the winding. The radiating surface is computed from the outside diameter of the coil which is 11 inches, it is therefore 11 times that given in the table or 1.386. In order to get the product of the two we multiply 1.386 by .66 which gives us .9148; 24,200 divided by this is equal to 26,465. Now in order to get the proper proportions the product of r.s. × R must be made 26,465 times greater than it is for the section we have considered. Since, however, every additional section adds equally to the resistance and to the radiating surface the product of the two increases directly as the square of the length, or, in this case, as the square of the turns. In order therefore to find how many turns per layer we must provide we extract the square root of 26,465 which is 162.96 (see table for method of obtaining square root). As there are 25 wires per inch we require 162.96 divided by 25 or 6.52 inches in length for the winding space to give us the proper radiation.

Let us now check up and see what we have obtained. The total radiating surface of the coil is 11 × 6.52 × 3.14 which equals 225.2 square inches. The total resistance is 163 × .66 which equals 107.58. In order to find the watts we divide $E^2=12{,}100$ by this and obtain 112.5 watts; 225.2 divided by this gives very nearly 2 inches of radiating surface per watt expended.

Owing to the fact that the number of turns per inch is not always as accurately given as in this case other calculations may not come out as closely correct, but they will be close enough for all practical purposes.

The case of a coil to be wound for a fixed current becomes very simple by the use of Table IV. This table gives in the three columns at the right marked cool, warm, hot, the squares of the currents permissible under the different conditions of heating given. The watts in any circuit, it is well known, are equal to the square of the current, multiplied by the resistance. If we assume that the radiating surface does not change we must see that $I^2 \times R$ is always the same no matter how many layers deep we may wind; that is, two layers must consume no more energy than one. Since in two layers R is double that of one, I^2 must be only half that of one layer. In other words, the current must be so reduced that it, squared, will amount to only half the square of the current for one layer. To find this current for any number of layers we divide the square of the current for one layer by the number of layers and extract the square root. It can be seen that we can turn this process about and in order to obtain the size of wire for a given current we need only to square the current and multiply by the number of layers. Having done this we compare the number so found with the numbers in whichever of the three columns we desire to work under and find the number nearest equal to it. Opposite the number under B. & S. will be found the proper size of wire for the depth of winding and the current considered.

As has been stated before, this current is based upon the assumption that the radiating surface does not change with different depths of winding. This condition is approximately fulfilled when the diameter of the spool is very large compared to the size of wire and the number of layers considered. Theoretically, by this formula the watts remain always the same; hence by comparing the actual radiating surface of the finished coil of many layers by that of a coil of one layer we can form some idea of what the excess of radiating surface will be. It will always be greater in the proportion, as the diameter of the finished coil is greater than that of the diameter of the spool.

Example: We have a current of 7 amperes from which we desire to obtain 900 ampere turns. The diameter of the spool is 8 inches and the winding is to be selected from the column "warm."

In a case of this kind we have nothing to do with the voltage. This is taken care of by an increase of E. M. F., which must be made in proportion to the added resistance to keep the current at its normal value. The diameter of the core also interests us only in so far as it affects the radiating surface if there are many layers.

We begin the calculation by trying what one layer will do for us. To this end we square 7, which gives us 49. Following the column "warm" downward we come to 40 and 59. In order to be on the safe side let us try the larger wire, as this will give us less heating than will the smaller; 59 corresponds to a No. 17 wire, which gives us (double cotton covered) 19 turns per inch. As we need 900 divided by 7, or 129 turns, we should require a coil equal to 129 divided by 19=6.7 inches in length. Let us now try 5 layers deep. We now have 49 times 5, which equals 245. Tracing down the same column and keeping on the safe side we come to 325, which corresponds to a number 12 wire. As this is 5 layers deep we need only 26 turns in each layer to make up the 129 turns, and as there are 11 turns per inch we shall need only 2.4 inches for the length of winding space.

As the winding depth of 5 layers corresponds to ½ inch very closely, the total diameter of our coil is very nearly 9 inches and the total radiating surface is about $9 \times 3.14 \times 2.4 = 67.82$ square inches. The length of a mean layer is about 8.5 inches and the resistance given in the table .00042. The total resistance is therefore $8.5 \times .00042 \times 2.4 \times 11 \times 5 = .47$, which, multiplied by the square of the current, 49, gives us 23.03 as the number of watts.

We have here a radiating surface much greater than we required, first, because we took a wire larger than indicated, and, second, because the depth of winding increases the outside diameter of the coil considerable over that of the inner. If instead of the 12 we had taken a number 13 we should have a radiating surface of about 60.79 and the watts would be about 28.42. This is still a little larger than required and we may take it, as a general rule, that wherever any considerable depth of winding is considered we may safely take a wire one size smaller than indicated.

From consideration of the foregoing we may now establish the following rules and formulæ for the table:

1. To find the smallest wire from which the required ampere turns can be obtained. The resistance R of the wire as given in the table equals $\frac{E}{a.t. \times D}$.

2. To find the number of layers multiply assumed depth of winding by the number of turns per inch of the wire in question.

3. To find the number of turns per layer to give required radiating surface n.t. $= \sqrt{\frac{E^2 \times a}{R \times l \times r.s \times D^1}}$

4. To find length in inches of coil divide result of formula 3 by number of turns per inch of wire in question.

5. To find total number of turns multiply result of formula 2 by that of 3.

FOR A FIXED CURRENT.

To find number of convolutions necessary divide number of ampere turns by the current.

To find smallest permissible wire for any depth of winding multiply the current to be used by itself and by the number of layers in depth of winding. Select the number nearest equal to this from one of the columns at the right of the table; opposite this number under B. & S. will be found the gauge number of the wire required. As a rule a wire one or two sizes smaller than indicated can be used.

SYMBOLS USED IN FORMULAS.

E = voltage.
a.t. = ampere turns.
D = mean diameter of winding.
R = resistance as given in table.
l = number of layers.
D^1 = total diameter of coil.
r.s. = radiating surface as given in table.
n.t. = number of turns per layer.
a = variable from 1 to 3 and equal to 2 for general purposes.

TYPES OF MAGNETS.

Figure 111 shows the commonest form of electromagnet in use. It is this type that is used for telegraph, telephone and all similar work where the armature is close to the poles and where action over an extended range is not necessary.

The windings for all types of magnets must be applied as illustrated in Figures 112 to 114. Figure 112 shows a view of the winding as it would appear to one looking at it from the end of the magnet. It will be noticed that it forms a spiral, half of which runs in opposition to the other.

Another way in which to familiarize oneself with the condition of the wires to insure the proper operation of a magnet when complete can be explained by reference to Figure 113. In order that all of the windings may tend to produce a circulation of the lines of force in the same general direction they must be applied to the two coils just as though they were all wound upon one coil and all in the same direction as in Figure 113.

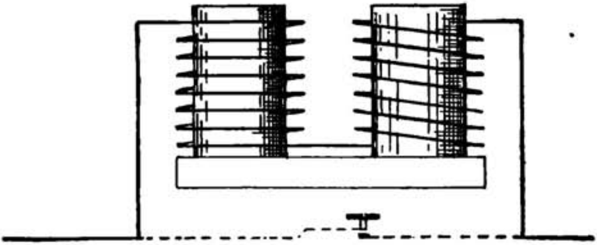


Figure 111.

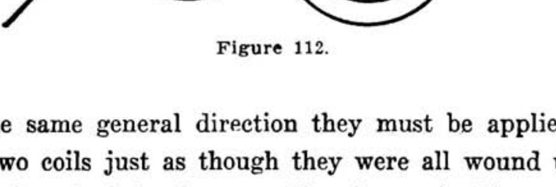


Figure 112.

If now the two coils illustrated in this figure are separated and set up on the yoke to form the coils of a complete magnet it will be seen that the windings will run as shown in Figure 114. Figure 114 has exactly the same wire on it as Figure 113 and is placed on in the same way, and consequently the lines of force produced will all be in the same general direction. The loop of wire at the bottom of magnet 2 is not neces-

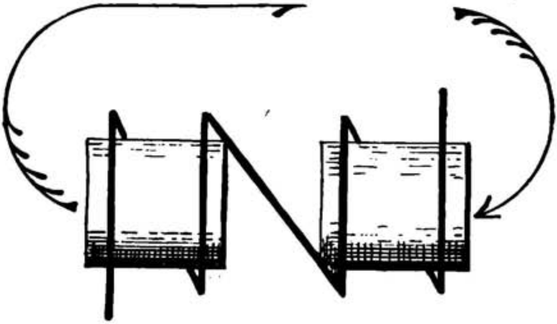


Figure 113.

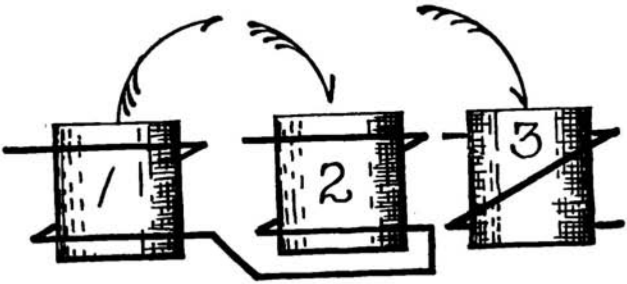


Figure 114.

sary; it is merely shown because it would come that way if Figure 113 were set up as is here shown. If magnet 1 were connected directly to the top of magnet 3 the result would be the same. It is also immaterial whether the winding runs to the right or to the left, or as shown in the figure, up or down, on the spool; the only point that must be observed is, the manner in which the current circulates around the magnet, which must always be as illustrated in Figure 112.

SPARKING.

In connection with all electro-magnets in which the current is often interrupted the sparking is a very important and troublesome item. To reduce damage from it to a minimum it is necessary to use platinum at all points where the break in the circuit occurs. Many schemes have been tried to lessen the troubles from this source, but we shall confine ourselves to dealing with the four most effective methods. The best method, where it can be applied, is that depicted in Figure 115. This is a differential magnet, provided with two coils wound in opposite direction, so that as long as current is flowing in both of them there is no magnetism. If now the current through one of the coils is interrupted the other coil remains alone in action and the magnetism appears as soon as the opposing magnetism disappears. With this winding when we break the circuit we destroy no lines of force, and consequently are not troubled with an induced E. M. F. and current which give us the spark. On the other hand, when we desire to destroy the magnetism we do so by closing an electric circuit and whatever induced currents there may be can circulate in the coils where they can do no harm.

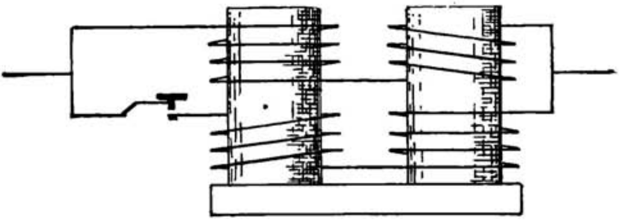


Figure 115.

The next method is that shown by the dotted lines in Figure 111. In this method instead of breaking the circuit of the magnet we shunt the current around it by closing the key. There is no spark when the magnetism is destroyed, but of course there is some sparking when the shunt circuit is opened and the current forced through the magnet.

Another method sometimes used consists in covering the core with a copper sheath before the winding is put on. When the current is interrupted the lines of force in the iron induce currents in the copper sheath, which in turn tend to keep up the magnetism, thus allowing it gradually to die out instead of being suddenly and totally destroyed.

Sometimes also a condenser is bridged across the break as shown in Figure 116. This takes up much of the current and lessens the sparking.

LIFTING MAGNET.

The general shape and arrangement of a lifting magnet is shown in Figure 117. For this purpose it is essential that the magnetic circuit be as good as possible and the pole pieces must be made to fit the pieces that are to be lifted as closely as possible. In any magnetic circuit of high efficiency anything that will introduce an airgap, ever so slight, will materially lessen the traction.

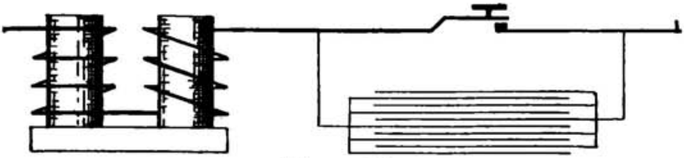


Figure 116.

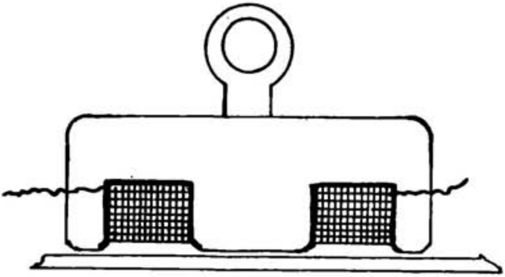


Figure 117.

It must be borne in mind that the traction or lifting power is in proportion to the square of the lines of force, and a little dirt the thickness of paper may in some cases result in a loss of half the lifting power of the magnet.

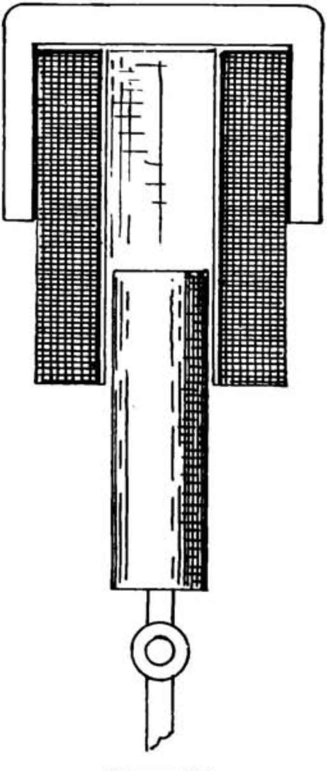


Figure 118.

MAGNETS FOR LONG RANGE OF ACTION.

Figures 118 to 120 show forms of magnets adapted for use where a considerable length of stroke is necessary. In such places the ordinary electro-magnet cannot be used because of the great airgap and the tendency of the lines of force to leak back instead of extending to the armature. In Figures 118 and 119 two solenoids are shown, one for a single plunger, and the other for a double. When current is turned on there is a strong suction, the magnetism tending, so to speak, to suck in the cores until they assume a position at which the magnetic circuit is as good as it can be with that particular coil and plunger. The general guiding principle which can be used here as well as in connection with all electromagnets is that the lines of force tend always to draw the iron of the magnetic circuit into such a position that

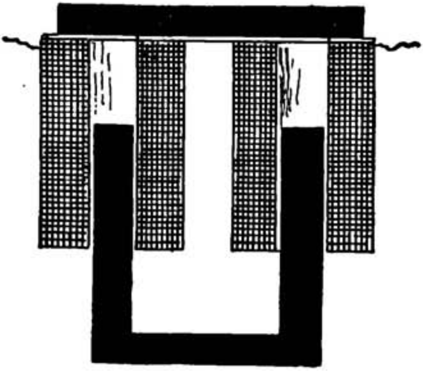


Figure 119.

it will accommodate the most of them, i. e., form the best possible path for them, and thus produce the greatest number.

MAGNET FOR QUICKEST ACTION.

For a magnet of this kind we must do just the opposite of what is essential in lifting and other power magnets. It is well known that every magnet possesses some inductance, and that this inductance is in proportion to the lines of force produced in it. If we have

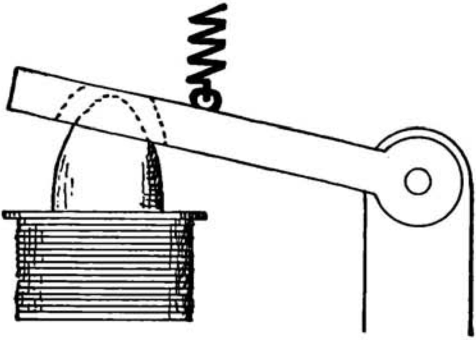


Figure 120.

a magnet of very high efficiency we shall have very great inductance and consequently a very great retardation of the current. This will give us a slow acting magnet. If instead of this we employ a magnet of low efficiency we shall have a low inductance and consequently there will be little retardation. Of course the energy used up in this case will be large compared to the results obtained. The case is analogous to that of a large and small ball striking a pin. The small ball requires little energy to move and imparts it all to the pin and comes to a stop when it strikes. This is a case of high efficiency, and the action is slow, for the ball must be brought in motion again. On the other hand, the large ball requires considerable energy to bring it into motion and when it finally strikes the pin the energy required to knock it over is so little compared to what is stored in it that the ball is not noticeably checked by it. In the same way a magnet so arranged that its counter E.M.F. or self-induction is equal to but a fraction of the total E.M.F. required in the circuit is the one best adapted for very quick work.

CHOKE OR RETARDATION COILS.

Coils for this purpose require a very good magnetic circuit. Other things being equal, the better the magnetic circuit the greater will be the reactance or choking effect.

MAGNET WINDING; PRACTICAL POINTS.

Before beginning the winding, the cores of all electromagnets should be well insulated. This is usually accomplished by placing one or more layers of paper around the iron core. If the magnet is to be subjected to high E.M.F.'s this insulating medium should be quite substantial and specially prepared. For ordinary purposes, however, almost any good paper will do. Layers of paper are also placed between the different layers of winding according to the needs of the case; for great potential differences, between each layer, and for smaller potentials, between every third or fourth layer. The paper between the layers also serves to keep the winding smooth and regular.

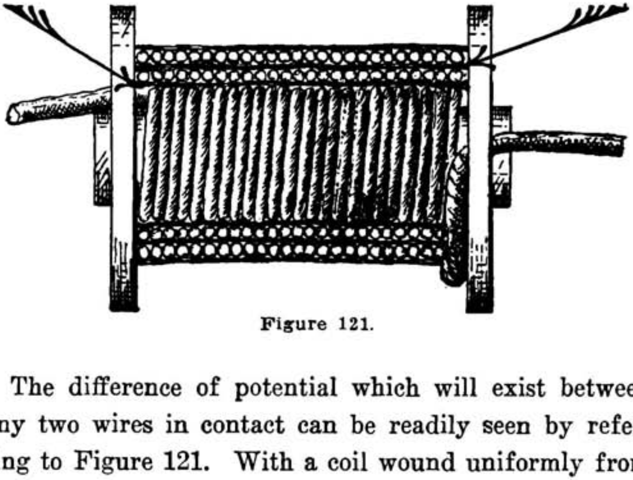


Figure 121.

The difference of potential which will exist between any two wires in contact can be readily seen by referring to Figure 121. With a coil wound uniformly from left to right and right to left the greatest difference of potential that can exist between any two wires is that between the two wires at the ends of the layers as shown by the arrows in the figure. The difference of potential which exists at these points can be determined by dividing the total difference of potential over the entire coil by the number of layers and multiplying by 2. As an example: If the voltage at the terminals of the three layers shown in Figure 121 is 100, the voltage between the two adjacent wires indicated by the arrows will be 66.6. The layers must, therefore, be insulated for this difference of potential.

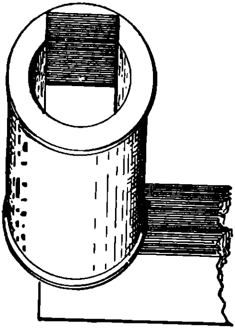


Figure 122.

As it is necessary to have laminated cores for alternating current magnets and as these cores are laminated as shown in Figure 122, the construction of a core of circular cross section would require numerous punchings of different shapes. For this reason and to make the cost of construction less, cores of square cross section are often used. The wires for this form of magnet are sometimes wound upon hollow spools of fiber and this afterward filled as full as possible by forcing as many of the punchings into it as it will hold.

The ordinary electro-magnet is wound in a machine similar to a lathe, the spool being centered and the wire guided into position by the hand of the operator. The device shown in Figure 123 is very useful in counting the number of turns. It is attached to the winding machine in such a manner that the spindle makes the same number of revolutions as the spool and the pointers on the dial revolve and indicate at any time the number of revolutions the spool has made. Other devices sometimes used automatically measure and record the length of wire wound on the spool.

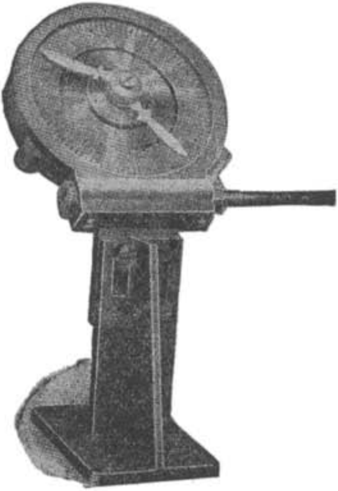


Figure 123.

Where magnets requiring a great number of turns, such as are to be used for high voltages, for instance, are to be wound, special winding machines are constructed. A mechanical guide is arranged to move the wire along the spool at the desired rate of speed so that the wire becomes properly spaced along the spool. This makes possible winding at a very high rate of speed and also allows of winding with bare wire, the wire being so spaced as to leave an air space between adjacent turns. Each layer of wire must be covered with a layer of paper to insulate the various layers. In the Varley winding bare wire is used, a layer of string or thread being wound on parallel with the wire, this serving to keep the adjacent wires separated. Sheets of insulat-

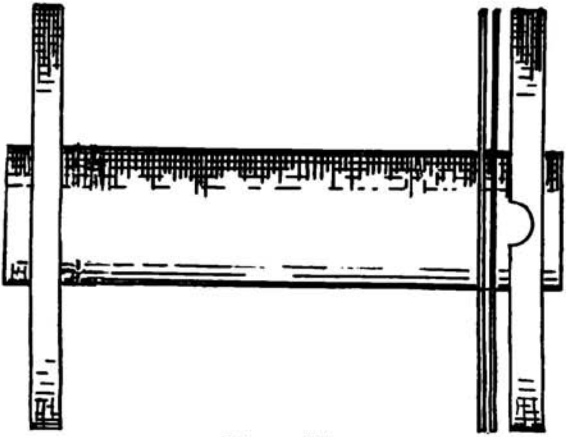


Figure 124.

ing material are placed between the adjacent layers and the wire thus becomes fully separated, although not in itself insulated.

Wire should always be applied to the core in such a manner as to avoid crossing wires, as would be the case if the wire from the bottom layer, Figure 121, was brought out inside the end pieces instead of passing through them. Another method of bringing out the wires from the lowest layer is shown in Figure 124. The two end washers are placed together and a hole drilled through them as shown in the figure. Other washers cut from cardboard or thin fiber are placed on the core between the two drilled washers. The wires leading from the inside layer are brought out through the drilled hole and the other washers then forced up against these wires, holding them in place. It is necessary, of course, in all cases to have the end washer either fit very tightly to the iron core or else to fasten it with shellac or cement.

When the magnet is wound with small wire it is well to solder a short length of stronger wire to the end of the winding and let this project from the end of the spool. The fine wires are very easily broken if, as is often the case, it is necessary to repeatedly disconnect them. If the wire from the inside layer breaks it may be necessary to entirely rewind the spool. Stranded wire, which is capable of considerable handling, is best tc use for this end connection. Another method consists in doubling up the end of the wire with which the coil is wound several times. The ends of the turned-up loops are then cleaned of insulation and soldered to the wire which is to be wound on and the wires twisted together, thus forming a flexible connection. With this method it will be seen that there is no break in the wire, as the wire which is wound on is also brought out in the twisted group. This is shown in Figure 125.

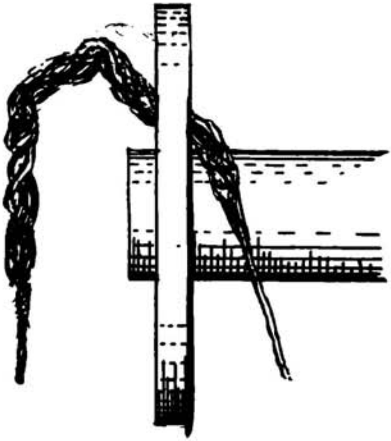


Figure 125.

Where it is necessary to make a joint in the wire with which a coil is being wound the ends should be twisted together and soldered. With fine wires a small piece of paper simply folded over the joint and held in place by the succeeding turns will provide all the insulation necessary, the ends of the wire at the joint being cut off close to the wire or otherwise disposed so that they will not cut through the paper covering. Special attention must be paid to the soldering and if the following points are observed satisfactory results will be obtained: The soldering iron should be clean and well tinned. To keep the iron in the proper condition it should be dipped in sal-ammoniac salts or a solution of sal-ammoniac and water just before the soldering is done. The sal-ammoniac destroys the oxide which gathers on the iron and thus allows the solder to entirely cover the copper. The iron should be hot; satisfactory work cannot be done with a cold iron. Great care should be exercised in the choice of a flux, as any flux containing an acid is bound to leave some of the acid on the wire after the soldering is done, and this acid, especially with small wires, is very apt to eat away the wire. If any doubt exists as to the flux used it is well to wash the joint with water after soldering. If the wires are tinned, a rosin flux should be used. This can do no harm even though some of the rosin is left on the wire.

Where large wires are used the ordinary Western Union joint cannot be used, as it would make too large an obstruction and could not be properly covered by the subsequent layers. A joint suitable for large wires is shown in Figure 126. A piece of copper is formed into a cylinder of sufficient size to cover the wire. This is then placed over the adjoining ends and the whole well soldered. The two ends of wire may be cut on a bevel and then wound with smaller wire and the whole soldered.

When, with differential windings, it is desired to have both windings have the same effect, they are wound on together, two wires at a time. It is well to take the wires for the same magnet from the same spool, as wires on different spools, even though marked the same size, often vary in diameter and resistance, while with the wire from one spool there is not liable to be much variation.

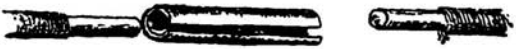


Figure 126.

A non-inductive winding, which is often used for resistance spool windings, consists of a double winding with one end of the winding closed. When it is desired to make a winding of this kind, enough wire is measured off to serve for the complete winding. This wire is then doubled together at the middle point and wound on the spool, the two wires being wound on at one time. It will be seen that when current is passed through the wire it will flow in opposite directions in the two wires lying side by side and no magnetism will result. This winding will therefore have no inductance, this point being especially advantageous in the case of resistance spool windings.

The insulation of the magnet winding is of importance and varies according to the purpose to which the magnet is to be put. If it is to be used in a dry place the insulating covering of the wire can be depended upon for proper insulation, while if the magnet is to be exposed to moisture special precautions must be taken to afford a good insulation. The covering of the wire and the paper used for separating the layers will both absorb moisture. Shellac is the common agent used for insulating purposes. Each layer of wire as it is wound on can be covered with shellac and the completed winding also covered. The coil should be thoroughly baked to drive out all moisture and to harden the shellac. The finished coils are sometimes submerged in a tank filled with insulating compound. When a very good insulation is desired the air is exhausted from the tank before the compound is let in, and after the coils are submerged, air pressure is applied to force the insulating compound into all the spaces between the windings.

German silver or iron wires are generally used for coils that are to be used for heating purposes. There are also special wires made to be used for this purpose which can be obtained from the various wire manufacturers. These wires are generally used bare, and for economy of space should be run close together. This can only be done by winding them upon a support that is very substantial and by winding the wires very tight. The metal of which the support consists should have as nearly as possible the same coefficient of expansion as the wire used. In order to effect the tight winding of the wire upon the support the winding is done in a lathe and the wire run through a number of tension wheels as indicated in Figure 127. Coils of this type are also formed by winding the wire tightly around an iron rod and then mounting them in suitable supports so that they are stretched out and adjacent turns somewhat separated.

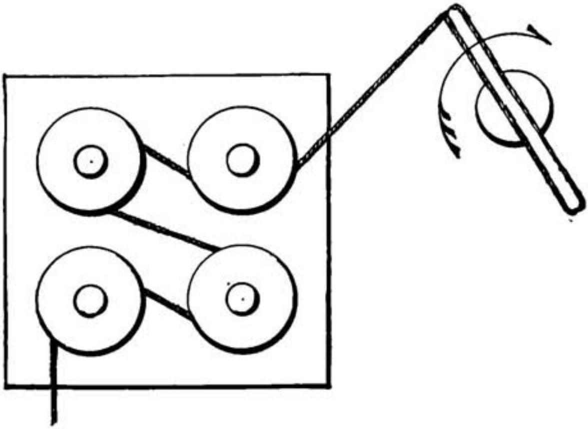


Figure 127.

The resistances of smaller wires as given in the tables furnished by the manufacturers vary considerably and it is not always safe to assume any given resistance in calculating the wire for a magnet. It is always more satisfactory to obtain a piece of the wire which it is intended to use and determine the exact resistance.

FACTS ABOUT ELECTRO-MAGNETS.

Heating.—The heat generated in the coils of a direct current electromagnet is proportional to the square of the current used.

It also varies directly as the square of the voltage and as the product of the current and voltage.

In alternating current magnets the heating is greater by an amount due to hysterisis and foucault currents.

The heating from hysterisis and foucault currents is furthermore much increased with an increase in the frequency.

Radiating Surface.—The radiating surface of coils must be taken as equal to the length times the circumference. The surface of the ends cannot be considered.

A radiating surface ranging from 1 to 3 square inches per watt of energy expended in the coils is necessary to limit the heating. The lower radiating surface is permissible only where the ventilation is extremely good or the current used only at intervals for a short time.

Magneto-Motive Force.—The magneto-motive force, or M.M.F., also known as "ampere turns," is equal to the product of the current and the number of turns of wire through which it passes around the coil.

Magnetic Reluctance.—This corresponds to resistance in the electric circuit and is similar in nature. It decreases as the cross-section of the core is increased and increases with the length. The reluctance of air is from 50 to 1,500 times greater than that of iron, the variation in the iron being due to the degree of saturation.

Sparking.—This is much greater where the M.M.F. is made up of a small current and a correspondingly large number of turns than it is with a large current and a small number of turns.

Inductance.—The inductance is also greater with many turns of wire than with a few. It also increases with an increase in the frequency and a betterment of the magnetic circuit.

Hysterisis.—This is one of the causes of the heating of the cores of alternating current magnets. It is lessened by selecting very soft annealed iron or steel. It is increased by imperfect iron or steel. It is further increased by an increase in the frequency of the reversal of current.

Foucault Currents.—Foucault currents are induced in the iron cores of alternating current magnets, and tend to heat it. They are prevented to a degree by laminated cores and their effect is greatly increased with an increase in the frequency.

Size of Wire.—A given number of ampere-turns (mean diameter of coil and voltage being fixed) can be obtained from a certain size of wire only.

The ampere-turns will remain the same no matter how many turns of the same size of wire are used so long as the voltage and the mean length of the turns are not changed.

To obtain an increase in the number of ampere-turns requires an increase in the diameter of the wire used.

To obtain the same number of ampere-turns with different mean diameters of winding, the cross-section of the wire must vary in the same proportion as the mean diameters of the coils.

Assuming that the insulation of all sizes of wire is in the same proportion to the diameter of the wire, the weight of copper in a coil of given dimensions is the same no matter what size of wire is used.

Energy Consumption.—From a certain size of wire we obtain a certain number of ampere-turns. We get the same effect from one turn as from thousands, but the greater the number of turns the lower will be the consumption of energy. Theoretically, magnetism can be produced without consumption of energy. In a given coil the consumption of energy will vary as the square of the voltage or as the square of the current used.

Resistance.—Neglecting the effect of the insulation upon the number of turns, the resistance of a coil of fixed dimensions will vary as the 4th power of the diameter of the wire.

The resistance of a coil of a given volume will also vary as the square of the number of turns.

It is often given as a rule for the winding of electromagnets that the resistance of the magnet or a number of them should be made equal to the resistance of the line and the battery. How far this is correct is illustrated in the following table. It will be seen that this rule is useful only in obtaining the maximum effect from a given battery and line, but does not take in the efficiency of operation at all. The table gives the results obtained from a given spool wound to the same volume with different sizes of wire.

Assumed voltage; 20 volts.
Resistance of line and battery 20 ohms.

B & S.	Resistance.	No of Turns.	Amperes.	Watts.	Amp Turns.	A. T. per Watt.
20	3.02	760	.87	17.4	661	38
22	7.22	1140	.73	14.6	832	57
24	17.04	1694	.54	10.8	915	85
26	39.6	2478	.33	6.6	818	124
28	90.0	3549	.18	3.6	639	177
30	182.4	4986	.10	2.0	499	249
32	440.9	6870	.043	.86	295	343
34	947.0	9272	.021	.42	194	462
36	1975	12160	.01	.20	122	608

Thickness of Insulation.—The average thickness of insulation for magnet wire is something like the following:

For armature winding an insulation consisting of one layer of cotton and one of silk is often used. The silk alone does not stay well on the sharp bends.

B & S Gauge.	Double cotton.	Single cotton.	Double silk.	Single silk.
20 to 40	8 mils.	4 mils.	4 mils.	2 mils.
10 to 20	10 mils.	5 mils.		
0 to 10	15 mils.	8 mils.		

CHAPTER XI.

USEFUL FORMULAS AND TABLES.

In the following formulas it is assumed that the wires lie squarely over one another in the coil, each wire fully occupying a space equal to the square of its diameter. As in most coils some insulating medium is placed between the different layers, this is about the condition which exists in practice.

The symbols used in the formulas are as follows:

d=diameter of wire, in inches, over insulation.
l=length of wire, on spool, in inches.
nt=number of turns.
r=resistance of one foot of wire.
rs=radiating surface.
B=diameter of core and insulation, in inches.
D=diameter over outside of completed winding in inches.
L=length of winding space on spool, in inches
N=depth of winding from core to outside, in inches.
W=weight of wire.
a, c, k=constants for use in the formula, given in the tables below. Each constant has a different value for each size and kind of wire used.

Number of turns in a given spool (see Figure 128):

$$nt = \frac{L \times N}{d^2}$$

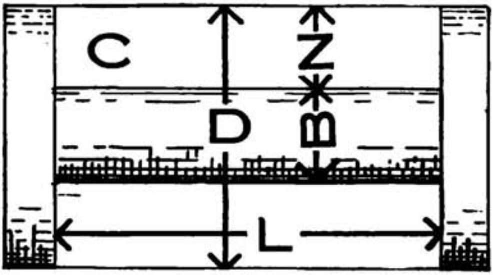


Figure 128.

Diameter of wire to give a certain number of turns:

$$d = \sqrt{\frac{L \times N}{nt}}$$

Cross-section of winding space, or $L \times N$, necessary to accommodate a certain number of turns of a given wire:

$L \times N = d^2 \times nt.$

Length of wire on a given spool:

$l = (D^2 - B^2) L \times k.$ See table below for value of ***k***.

Weight of wire on a given spool:

$W = (D^2 - B^2) L \times c.$ See table below for value of ***c***.

Resistance of wire on a given spool:

$R = (D^2 - B^2) L \times a.$ See table below for value of ***a***.

Radiating surface for a given spool:

$rs = D \times 3.14 \times L.$

TABLE OF CONSTANTS.

B. & S. Gauge.	k Constant for Length.			c Constant for Weight.			a Constant for Resistance.		
	Double Cotton	Single Cotton	Single Silk	Double Cotton	Single Cotton	Single Silk	Double Cotton	Single Cotton	Single Silk
20	40.9	50.4	56.7	.137	.162	.177	.415	.512	.576
21	50.4	64.1	72.7				.638	.812	.920
22	60.2	78.0	89.7				.97	1.257	1.445
23	68.3	89.7	104.7				1.387	1.82	2.08
24	83.6	113.5	135.	.1115	.149	.169	2.14	2.91	3.46
25	97.2	135.	163.				3.14	4.36	5.27
26	114.	163.	202.				4.65	5.65	8.24
27	135.	202.	255.				6.94	11.75	13.1
28	148.	226.	291.	.0845	.122	.148	9.60	14.62	18.82
29	182.	291.	387.				14.85	23.7	31.6
30	201.	334.	454.				20.7	34.4	46.8
31	226.	387.	542.				29.36	50.25	70.4
32	255.	454.	655.	.0687	.1045	.132	41.8	74.4	107.2
33	291.	542.	812.				60.33	114.5	168.
34	334.	655.	1023.				87.1	170.5	266.5
35	354.	712.	1140.				116.2	234.	374.8
36	387.	811.	1340.	.0492	.0825	.1115	160.	335.5	555.
37	422.	897.	1582.				220.5	468.	806.
38	457.	1023.	1825.				308.	674.	1192.
39	496.	1170.	2165.				412.	972.	1795.
40	532.	1300.	2525.	.038	.0615	.0888	557.	1360.	2645.

TABLES.

TABLES OF SQUARE ROOTS.

The tables of square roots given in this chapter will greatly facilitate calculations involving the squaring of numbers or the extraction of square roots. This becomes frequently necessary in armature and magnet calculations.

There are two tables, each covering two pages. One of these tables is to be used for numbers from .1 to 99.9, inclusive, and the other for numbers from 1 to 999.

The first one or two figures of every number between these limits is given in the first left-hand column. If there are three figures in the number the third one will be found at the head of one of the columns to the right. For instance, if the number of which we desire to find the square root is 233, we find 23 in the first column at the left and the remaining 3 in the column at the right headed "3." If the number of which we wish to find the square root consists of only two numbers, we find the first number in the column at the left and the remaining number in one of the columns at the right For instance, if we have the number 36, we go down the first column to figure 3 and in line with this figure and under the column headed "6" we will find the square root.

The root of a whole number consists of a whole number and a decimal. The whole number is found under the column headed "0" and the decimal under one of the columns at the right. For instance, the square root of 233 is 15.26, the whole number (15) being found under the column headed "0" and the decimal (.26) under the column headed "3." The whole numbers in the column headed "0" hold for all the numbers following until a larger whole number is given. Wherever in any line the numbers are underlined these numbers belong to the next higher whole number. For instance, the square root of 259 is 16.09, the whole number (16) being found ahead of this number instead of the number following it.

Whenever the root of a number carried to more decimal points, or smaller than any number given in the table, is wanted, we may multiply this number by 100, find the root of this product and divide it by 10; the result will be the square root desired. Example: Find the square root of .475. Moving the decimal point two figures to the right, which effects the multiplication, we have 47.5. The square root of this is 6.89. Moving the decimal point one figure to the left, we have .689, which is the square root of .475.

In case multiplication by 100 does not bring the number within range of the tables, multiplication by any other number will do as well, provided that the subsequent division is made by the square root of the multiplier.

If the number is larger than any given in the table we reverse the process and divide by some convenient number and multiply by the root of that number.

SQUARE ROOTS 1. TO 999.

	0	1	2	3	4	5	6	7	8	9
0	0.00	1.00	1.41	1.73	2.00	2.24	2.45	2.65	2.83	3.00
1	3.16	32	46	61	74	87	00	12	24	36
2	4.47	58	69	80	90	00	10	20	29	39
3	5.48	57	66	74	83	92	00	08	16	25
4	6.32	40	48	56	63	71	78	86	93	00
5	7.07	14	21	28	35	42	48	55	62	68
6	75	81	87	94	00	06	12	19	25	31
7	8.37	43	49	54	60	66	72	78	83	89
8	94	00	06	11	16	22	27	33	38	43
9	9.49	54	59	64	70	75	80	85	90	95
10	10.00	05	10	15	20	25	30	34	39	44
11	48	54	58	63	67	72	77	82	86	91
12	95	00	05	09	14	18	23	27	31	36
13	11.40	45	49	53	58	62	66	70	75	79
14	83	87	92	96	00	04	08	12	17	21
15	12.25	29	33	37	41	45	49	53	57	61
16	65	69	73	77	81	85	88	92	96	00
17	13.04	08	11	15	19	23	27	30	34	38
18	42	45	49	53	56	60	64	67	71	75
19	78	82	86	89	93	96	00	04	07	11
20	14.14	18	21	25	28	32	35	39	42	46
21	49	53	56	59	63	66	70	73	76	80
22	83	87	90	93	97	00	03	07	10	13
23	15.16	20	23	26	29	33	36	39	43	46
24	49	52	56	59	62	65	68	72	75	78
25	81	84	87	91	94	97	00	03	06	09
26	16.12	16	18	22	25	28	31	34	37	40
27	43	46	49	52	55	58	61	64	67	70
28	73	76	79	82	85	88	91	94	97	00
29	17.03	06	09	12	15	18	20	23	26	29
30	32	35	38	41	44	46	49	52	55	58
31	61	64	66	69	72	75	78	80	83	86
32	89	92	94	97	00	03	06	08	11	14
33	18.16	19	22	25	28	30	33	36	38	41
34	44	47	49	52	55	57	60	63	65	68
35	71	74	76	79	81	84	87	89	92	95
36	97	00	03	05	08	11	13	16	18	21
37	19.24	26	29	31	34	36	39	42	44	47
38	49	52	54	57	60	62	65	67	70	72
39	75	77	80	82	85	87	90	92	95	98
40	20.00	03	05	07	10	12	15	17	20	22
41	25	27	30	32	35	37	40	42	45	47
42	49	52	54	57	59	62	64	66	69	71
43	74	76	78	81	83	86	88	90	93	95
44	98	00	02	05	07	09	12	14	17	19
45	21.21	24	26	28	31	33	35	38	40	42
46	45	47	49	52	54	56	59	61	63	66
47	68	70	73	75	77	79	82	84	86	89
48	91	93	95	98	00	02	05	07	10	11
49	22.14	16	18	20	23	25	27	29	32	34

SQUARE ROOTS 1. TO 999.

	0	1	2	3	4	5	6	7	8	9
50	22.36	38	40	43	45	47	50	52	54	56
51	58	61	63	65	67	69	72	74	76	78
52	80	83	85	87	89	91	93	96	98	00
53	23.02	04	07	09	11	13	15	17	19	22
54	24	26	28	30	32	35	87	39	41	43
55	45	47	49	52	54	56	58	60	62	64
56	66	69	71	73	75	77	79	81	83	85
57	87	90	92	94	96	98	00	02	04	06
58	24.08	10	12	15	17	19	21	23	25	27
59	29	31	33	35	37	39	41	43	45	47
60	50	51	54	56	58	60	62	64	66	68
61	70	72	74	76	78	80	82	84	86	88
62	90	92	94	96	98	00	02	04	06	08
63	25.10	12	14	16	18	20	22	24	26	28
64	30	32	34	36	38	40	42	44	46	48
65	50	51	53	55	57	59	61	63	65	67
66	69	71	73	75	77	79	81	83	85	87
67	89	90	92	94	96	98	00	02	04	06
68	26.08	10	12	13	15	17	19	21	23	25
69	27	29	31	32	34	36	38	40	42	44
70	46	48	50	51	53	55	57	59	61	63
71	65	66	68	70	72	74	76	78	80	81
72	83	85	87	89	91	93	94	96	98	00
73	27.02	04	06	07	09	11	13	15	17	18
74	20	22	24	26	28	29	31	33	35	37
75	39	40	42	44	46	48	50	51	53	55
76	57	59	60	62	64	66	68	69	71	73
77	75	77	78	80	82	84	86	87	89	91
78	93	95	96	98	00	02	04	05	07	09
79	28.10	13	14	16	18	20	21	23	25	27
80	28	30	32	34	35	37	39	41	43	44
81	46	48	50	51	53	55	57	58	60	62
82	64	65	67	69	71	72	74	76	78	79
83	81	83	84	86	88	90	91	93	95	97
84	98	00	02	03	05	07	09	10	12	14
85	29.15	17	19	21	22	24	26	27	29	31
86	33	34	36	38	39	41	43	44	46	48
87	50	51	53	55	57	58	60	61	63	65
88	66	68	70	72	73	75	77	78	80	82
89	83	85	87	88	90	92	93	95	97	98
90	30.00	02	03	05	07	08	10	12	13	15
91	17	18	20	22	23	25	27	28	30	32
92	33	35	36	38	40	41	43	45	47	48
93	50	51	53	55	56	58	59	61	63	64
94	66	68	69	71	72	74	76	77	79	81
95	82	84	85	87	89	90	92	94	95	97
96	99	00	02	03	05	06	08	10	11	13
97	31.14	16	18	19	21	23	24	26	27	29
98	31	32	34	35	37	38	40	42	43	45
99	47	48	50	51	53	54	56	58	59	61

SQUARE ROOTS .1 to 99.9

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0		.32	.45	.55	.63	.71	.77	.84	.89	.95
1	1.00	05	10	14	18	22	26	30	34	38
2	41	45	48	52	55	58	61	64	67	70
3	73	76	79	82	84	87	89	92	95	97
4	2.00	02	05	07	10	12	14	17	19	21
5	24	26	28	30	32	35	37	39	41	43
6	45	47	49	51	53	55	57	59	61	63
7	65	66	68	70	72	74	76	77	79	81
8	83	85	86	88	90	92	93	95	97	98
9	3.00	02	03	05	07	08	10	11	13	15
10	16	18	19	21	22	24	26	27	29	30
11	32	33	35	36	38	39	41	42	44	45
12	46	48	49	51	52	54	55	56	58	59
13	61	62	63	65	66	67	69	70	71	73
14	74	76	77	78	79	81	82	83	85	86
15	87	89	90	91	92	94	95	96	97	99
16	4.00	01	02	04	05	06	07	09	10	11
17	12	13	15	16	17	18	20	21	22	23
18	24	25	27	28	29	30	31	32	34	35
19	36	37	38	39	40	42	43	44	45	46
20	47	48	49	50	52	53	54	55	56	57
21	58	59	60	62	63	64	65	66	67	68
22	69	70	71	72	73	74	75	76	77	79
23	80	81	82	83	84	85	86	87	88	89
24	90	91	92	93	94	95	96	97	98	99
25	5.00	01	02	03	04	05	06	07	08	09
26	10	11	12	13	14	15	16	17	18	19
27	20	21	22	22	23	24	25	26	27	28
28	29	30	31	32	33	34	35	36	37	38
29	39	39	40	41	42	43	44	45	46	47
30	47	48	50	50	51	52	53	54	55	56
31	57	58	59	59	60	61	62	63	64	65
32	66	67	67	68	69	70	71	72	73	74
33	74	75	76	77	78	79	80	80	81	82
34	83	84	85	86	87	87	88	89	90	91
35	91	92	93	94	95	96	97	97	98	99
36	6.00	01	02	02	03	04	05	06	07	07
37	08	09	10	11	12	12	13	14	15	16
38	16	17	18	19	20	20	21	22	23	24
39	25	25	26	27	28	28	29	30	31	32
40	32	33	34	35	36	36	37	38	39	40
41	40	41	42	43	43	44	45	46	47	47
42	48	49	50	50	51	52	53	53	54	55
43	56	57	57	58	59	60	60	61	62	63
44	63	64	65	66	66	67	68	69	69	70
45	71	72	72	73	74	75	75	76	77	78
46	78	79	80	80	81	82	83	83	84	85
47	86	86	87	88	88	89	90	91	91	92
48	93	94	94	95	96	96	97	98	99	99
49	7.00	01	01	02	03	04	04	05	06	06

Square Roots .1 to 99.9

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
50	7.07	08	09	09	10	11	11	12	13	13
51	14	15	16	16	17	18	18	19	20	20
52	21	22	23	23	24	25	25	26	27	27
53	28	29	29	30	31	31	32	33	33	34
54	35	36	36	37	38	38	39	40	40	41
55	42	42	43	44	44	45	46	46	47	48
56	48	49	50	50	51	52	52	53	54	54
57	55	56	56	57	58	58	59	60	60	61
58	62	62	63	64	64	65	66	66	67	67
59	68	69	69	70	70	71	72	73	73	74
60	75	75	76	77	77	78	78	79	80	80
61	81	82	82	83	84	84	85	85	86	87
62	87	88	89	89	90	91	91	92	92	93
63	93	94	95	96	96	97	98	98	99	99
64	8.00	01	01	02	03	03	04	04	05	06
65	06	07	07	08	09	09	10	11	11	12
66	12	13	14	14	15	15	16	17	17	18
67	18	19	20	20	21	22	22	23	23	24
68	25	25	26	26	27	28	28	29	29	30
69	31	31	32	32	33	34	34	35	35	36
70	37	37	38	38	39	40	40	41	41	42
71	43	43	44	44	45	46	46	47	47	48
72	49	49	50	50	51	51	52	53	53	54
73	54	55	56	56	57	57	58	58	59	60
74	60	61	61	62	63	63	64	64	65	65
75	66	67	67	68	68	69	69	70	71	71
76	72	72	73	74	74	75	75	76	76	77
77	78	78	79	79	80	80	81	81	82	83
78	83	84	84	85	85	86	87	87	88	88
79	89	89	90	91	91	92	92	93	93	94
80	94	95	96	96	97	97	98	98	99	99
81	9.00	01	01	02	02	03	03	04	04	05
82	06	06	07	07	08	08	09	09	10	10
83	11	12	12	13	13	14	14	15	15	16
84	17	17	18	18	19	19	20	20	21	21
85	22	23	23	24	24	25	25	26	26	27
86	27	28	28	29	30	30	31	31	32	32
87	33	33	34	34	35	35	36	36	37	38
88	38	39	39	40	40	41	41	42	42	43
89	43	44	44	45	46	46	47	47	48	48
90	49	49	50	50	51	51	52	52	53	53
91	54	54	55	56	56	57	57	58	58	59
92	59	60	60	61	61	62	62	63	63	64
93	64	65	65	66	66	67	67	68	69	69
94	70	70	71	71	72	72	73	73	74	74
95	75	75	76	76	77	77	78	78	79	79
96	80	80	81	81	82	82	83	83	84	84
97	85	85	86	86	87	87	88	88	89	89
98	90	90	91	91	92	92	93	93	94	94
99	95	95	96	96	97	98	98	99	99	99

COPPER WIRE TABLE.

Giving Weights of Bare Wires at 68° F., for A. W. G. (Brown & Sharpe.)

A.W.G.	DIAMETER	AREA	WEIGHT	
B. & S.	Inches	Circular Mils.	Lbs. Per Foot	Lbs. Per Ohm
0000	.460	211,600.	.6405	13,090.
000	.4096	167,800.	.5080	8,232.
00	.3648	133,100.	.4028	5,177.
0	.3249	105,500.	.3195	3,256.
1	.2893	83,690.	.2533	2,048.
2	.2576	66,370.	.2009	1,288.
3	.2294	52,630.	.1593	810.0
4	.2043	41,740.	.1264	509.4
5	.1819	33,100.	.1002	320.4
6	.1620	26,250.	.07946	201.5
7	.1413	20,820.	.06302	126.7
8	.1285	16,510.	.04998	79.69
9	.1144	13,090.	.03963	50.12
10	.1019	10,380.	.03143	31.52
11	.09074	8,234.	.02493	19 82
12	.08081	6,530.	.01977	12.47
13	.07196	5,178.	.01568	7.840
14	.06408	4,107.	.01243	4 931
15	.05707	3,257.	.009858	3.101
16	.05082	2,583.	.007818	1.950
17	.04526	2,048.	.006200	1.226
18	.04030	1,624.	.004917	.7713
19	.03589	1,288.	.003899	.4851
20	.03196	1,022.	.003092	.3051
21	.02846	810.1	.002452	.1919
22	.02535	642.4	.001945	.1207
23	.02257	509.5	.001542	.07589
24	.02010	404.0	.001223	.04773
25	.01790	320.4	.0009699	.03002
26	.01594	254.1	.0007692	.01888
27	.0142	201.5	.0006100	.01187
28	.01264	159.8	.0004837	.007466
29	.01126	126.7	.0003836	.004696
30	.01003	100 5	.0003042	.002953
31	.008928	79.70	.0002413	.001857
32	.007950	63.21	.0001913	.001168
33	.007080	50.13	.0001517	.0007346
34	.006305	39.75	.0001203	.0004620
35	.005615	31.52	.00009543	.0002905
36	.0050	25.0	.00007568	.0001827
37	.004453	19.83	.00006001	.0001149
38	.003965	15.72	.00004759	.00007210
39	.003531	12.47	.00003774	.00004545
40	.003145	9.888	.00002993	.00002858

COPPER WIRE TABLE.

Giving Lengths, and Resistances of Bare Wire at 68° F., of Matthiessen's Standard Conductivity, for A. W. G.

(Brown & Sharpe.)

A. W. G.	LENGTH		RESISTANCE	
B. & S.	Feet Per Lb.	Feet Per Ohm	Ohms Per Lb.	Ohms Per Foot
0000	1.561	20,440.	.00007639	.0000489
000	1.969	16,210.	.0001215	.0000617
00	2.482	12,850.	.0001931	.0000778
0	3.130	10,190.	.0003071	.0000981
1	3.947	8,083.	.0004883	.0001237
2	4.977	6,410.	.0007765	.0001560
3	6.276	5,084.	.001235	.0001967
4	7.914	4,031.	.001963	.0002486
5	9.980	3,197.	.003122	.0003128
6	2.58	2,535.	.004963	.0003944
7	15.87	2,011.	.007892	.0004973
8	20.01	1,595.	.01255	.0006271
9	25.23	1,265.	.01995	.0007908
10	31.82	1,003.	.03173	.0009972
11	40.12	795.3	.05045	.001257
12	50.59	630.7	.08022	.001586
13	63.79	500.1	.1276	.001999
14	80.44	396.6	.2028	.002521
15	101.4	314.5	.3225	.003179
16	127.9	249.4	.5128	.004009
17	161.3	197.8	.8153	.005055
18	203.4	156.9	1.296	.006374
19	256.5	124.4	2.061	.008038
20	323.4	98.66	3.278	.01014
21	407.8	78.24	5.212	.01278
22	514.2	62.05	8.287	.01612
23	648.4	49.21	13.18	.02032
24	817.6	39.02	20.95	.02563
25	1,031.	30.95	33.32	.03231
26	1,300.	24.54	52.97	.04075
27	1,639.	19.46	84.23	.05138
28	2,067.	15.43	133.9	.06479
29	2,607.	12.24	213.0	.08170
30	3,287.	9.707	338.6	.1030
31	4,145.	7.698	538.4	.1299
32	5,227.	6.105	856.2	.1638
33	6,591.	4.841	1,361.	.2066
34	8,311.	3.839	2,165.	.2605
35	10,480.	3.045	3,441.	.3284
36	13,210.	2.414	5,473.	.4142
37	16,660.	1.915	8,702.	.5222
38	21,010.	1.519	13,870.	.6585
39	26,500.	1.204	22,000.	.8304
40	33,410.	0.9550	34,980.	1.047

TABLE FOR INSULATED COPPER WIRE. (Belden Manufacturing Co.)

B. & S. Gauge	Single Cotton, Total Insulation Thickness 4 Mils.		Double Cotton, Total Insulation Thickness 8 Mils.		Single Silk, Total Insulation Thickness 1 3-4 Mils.		Double Silk, Total Insulation Thickness 4 Mils.	
	Ohms per pound	Feet per pound	Ohms per pound	Feet per pound	Ohms per pound	Feet per pound	Ohms per pound	Feet per pound
20	3.15	311	3.02	298	3.24	319	3.18	312
21	4.99	389	4.72	370	5.12	403	5.03	389
22	7.88	488	7.44	461	8.15	503	7.96	493
23	12.44	612	11.7	584	12.92	636	12.65	631
24	19.55	762	18.25	745	20.50	800	19.95	779
25	30.8	957	28.45	903	32.50	1005	31.5	966
26	48.6	1192	44.3	1118	51.29	1265	49.7	1202
27	76.45	1488	68.8	1422	82.00	1590	78.3	1542
28	120.	1852	106.5	1759	129.00	1972	123.5	1917
29	188.5	2375	164.	2207	205.00	2570	194.	2485
30	294.6	2860	252.	2534	328.5	3145	306.5	2909
31	460.5	3800	384.5	2768	512.3	3943	477.	3683
32	716.	4375	585.	3737	810.0	4950	747.	4654
33	1117.	5390	880.	4697	1277.5	6180	1165.	5689
34	1720.	8580	1315.	6168	2018.	7740	1810.	7111
35	2642.	8050	1960.	6737	3175.	9680	2820.	8534
36	4060.	9820	2890.	7877	4970.	12000	4340.	10039
37	6190.	11860	4230.	9309	7940.	15000	6660.	10666
38	9440.	14300	6150.	10666	12320.	18660	10250.	14222
39	14420.	17130	8850.	11907	19200.	23150	15600.	16516
40	22600.	21590	12500.	14222	30200.	28700	23650.	21333

TABLE OF DIAMETERS (d) AND SQUARE OF DIAMETERS (d^2) FOR INSULATED COPPER WIRE.

B. & S.	Double Cotton		Single Cotton		Single Silk	
	d	d^2	d	d^2	d	d^2
20	.040	.0016	.036	.001296	.034	.001156
21	.036	.0013	.032	.00102	.030	.0009
22	.033	.00109	.029	.00084	.027	.00073
23	.031	.00096	.027	.00073	.025	.000625
24	.028	.000784	.024	.000576	.022	.000484
25	.026	.000675	.022	.000484	.020	.0004
26	.024	.000575	.020	.0004	.018	.000324
27	.022	.000484	.018	.000324	.016	.000256
28	.021	.000441	.017	.000289	.015	.000225
29	.019	.00036	.015	.000225	.013	.000169
30	.018	.000324	.014	.000196	.012	.000144
31	.017	.000289	.013	.000169	.011	.000121
32	.016	.000256	.012	.000144	.010	.000100
33	.015	.000225	.011	.000121	.009	.000081
34	.014	.000196	.010	.000100	.008	.000064
35	.0136	.000185	.0096	.000092	.0076	.0000576
36	.013	.000169	.009	.000081	.007	.000049
37	.0124	.000155	.00845	.000073	.00645	.0000415
38	.012	.000143	.008	.000064	.006	.0000362
39	.0115	.000132	.0075	.000056	.0055	.0000303
40	.0111	.000123	.0071	.0000504	.0051	.000026

CURRENT CARRYING CAPACITY OF 18 PER CENT GERMAN SILVER.

B. & S. Gauge	TEMPERATURE RISE BARE CONDUCTOR IN AIR					
	100° F	200° F	300° F	400° F	500° F	600° F
10	18.6 A	26.3 A	32.2 A	37. A	41.5 A	45.5 A
11	16.1	22.7	27.9	32.2	36.0	39.5
12	13.3	18.8	23.0	26.6	29.7	32.5
13	11.3	16.0	19.5	22.6	25.2	27.6
14	9.4	13.3	16.3	18.8	21.0	23.0
15	7.9	11.2	13.7	15.8	17.7	19.3
16	6.6	9.3	11.5	13.2	14.8	16.2
17	5.5	7.8	9.5	11.0	12.3	13.5
18	4.7	6.6	8.1	9.4	10.5	11.5
19	3.8	5.4	6.6	7.6	8.5	9.3
20	3.3	4.7	5.7	6.6	7.4	8.1
21	2.8	4.0	4.9	5.6	6.3	6.9
22	2.3	3.3	4.0	4.6	5.1	5.6
23	1.95	2.8	3.4	3.9	4.4	4.8
24	1.63	2.3	2.8	3.3	3.7	4.0
25	1.39	2.0	2.4	2.8	3.1	3.4
26	1.17	1.7	2.0	2.3	2.6	2.9
27	1.00	1.4	1.7	2.0	2.2	2.5
28	.83	1.9	1.5	1.7	1.9	2.0
29	.73	1.0	1.3	1.5	1.6	1.8
30	.58	.82	1.0	1.2	1.3	1.4
31	.49	.69	.85	.98	1.1	1.2
32	.41	.58	.71	.82	.92	1.0
33	.35	.50	.61	.70	.78	.86
34	.29	.41	.50	.58	.65	.71
35	.25	.35	.43	.49	.55	.60
36	.21	.29	.36	.41	.46	.50
37	.17	.25	.30	.35	.39	.43
38	.14	.20	.25	.29	.32	.35
39	.125	.18	.22	.25	.28	.31
40	.105	.15	.19	.21	.24	.26

For Iron multiply these values by 1.71.

For 30 per cent German Silver multiply these values by .8

TABLE OF WIRE AND SHEET METAL GAUGES.

(The United States Standard Gauge—U. S. S.—has been legalized by Act of Congress as a standard for sheet and plate iron and steel.)

No.	B. & S.	U. S. Standard	Birmingham	No.	B. & S.	U. S. Standard	Birmingham
0000	.46000	.40625	.454	19	.03589	.04375	.042
000	.40964	.375	.425	20	.03196	.0375	.035
00	.36480	.34375	.380	21	.02846	.03437	.032
0	.32486	.3125	.340	22	.02535	.03125	.028
1	.28930	.28125	.300	23	.02257	.02812	.025
2	.25763	.26562	.284	24	.02010	.025	.022
3	.22942	.25	.259	25	.01790	.02187	.020
4	.20431	.23437	.238	26	.01594	.01875	.018
5	.18194	.21875	.220	27	.01420	.01718	.016
6	.16202	.20312	.203	28	.01264	.01562	.014
7	.14428	.1875	.180	29	.01126	.01406	.013
8	.12849	.17187	.165	30	.01003	.0125	.012
9	.11442	.15625	.148	31	.00893	.01094	.010
10	.10190	.14062	.134	32	.00795	.01016	.009
11	.09074	.125	.120	33	.00708	.00937	.008
12	.08081	.10937	.109	34	.00630	.00859	.007
13	.07196	.09375	.095	35	.00561	.00781	.005
14	.06408	.07812	.083	36	.005	.00703	.004
15	.05707	.07013	.072	37	.00445	.00664	
16	.05082	.0625	.065	38	.00396	.00625	
17	.04526	.05625	.058	39	.00353		
18	.04030	.05	.049	40	.00314		

TABLE SHOWING THE CURRENTS WHICH WILL FUSE WIRES OF DIFFERENT SUBSTANCES.

B. & S. Gauge.	Copper.	German Silver.	Iron.
10	333.	170.	102.3
11	284.	146.	86.
12	236.	120.5	72.6
13	200.0	102.6	63.
14	165.7	84.6	50.9
15	129.	71.2	42.1
16	117.7	60.1	36.1
17	99.	50.4	32.6
18	81.9	41.8	25.2
19	66.7	34.2	20.2
20	58.5	29.9	18.
21	49.3	25.3	14.9
22	41.1	21.	12.4
23	34.5	17.7	10.9
24	28.9	14.8	8.9
25	24.6	12.6	7.46
26	20.7	10.6	6.4
27	17.7	9.1	5.36
28	14.5	7.4	4.5
29	12.5	6.41	3.79
30	10.2	5.2	3.1
31	8.75	4.49	2.65
32	7.3	3.7	2.3
33	6.19	3.18	1.88
34	5.1	2.6	1.6
35	4.37	2.24	1.33
36	3.6	1.8	1.1
37	3.08	1.56	.93
38	2.52	1.30	.76
39	2.20	1.11	.67
40	1.84	.95	.55

The above table is calculated from the well known formula due to W. H. Preece, F. R. S.

TABLE FOR DETERMINING MEAN LENGTH OF TURNS.

DOUBLE COTTON COVERED WIRE.

B. & S.	Ampere Turns 1 Volt, 1 Inch.	Diameter D. C. C.	One-half Number of Layers in Coil.							
			2	4	6	8	10	14	18	24
40	11.4	.0111	.022	.067	.111	.155	.200	.289	.377	.511
39	14.4	.0115	.023	.069	.115	.161	.207	.299	.391	.529
38	18.2	.0120	.024	.072	.120	.168	.216	.312	.408	.552
37	22.9	.0124	.025	.075	.125	.175	.225	.325	.425	.575
36	28.9	.0130	.026	.078	.130	.182	.234	.338	.442	.598
35	36.8	.0136	.027	.081	.135	.189	.243	.351	.459	.621
34	46.1	.0140	.028	.084	.140	.196	.252	.364	.476	.664
33	58.1	.0150	.030	.090	.150	.210	.270	.390	.510	.690
32	73.2	.0160	.032	.096	.160	.224	.288	.416	.544	.736
31	92.4	.0170	.034	.102	.170	.238	.306	.442	.578	.782
30	116.	.0180	.036	.108	.180	.252	.324	.468	.612	.828
29	147.	.0190	.038	.114	.190	.266	.342	.494	.646	.874
28	185.	.0210	.042	.126	.210	.294	.378	.546	.714	.966
27	233.	.0220	.044	.132	.220	.308	.396	.572	.748	1.01
26	293.	.0240	.048	.144	.240	.336	.432	.624	.816	1.10
25	371.	.0260	.052	.156	.260	.364	.468	.676	.884	1.20
24	461.	.0280	.056	.168	.280	.392	.504	.728	.952	1.29
23	591.	.0310	.062	.186	.310	.434	.558	.806	1.05	1.43
22	745.	.0330	.066	.198	.330	.462	.594	.858	1.12	1.52
21	938.	.0360	.072	.216	.360	.504	.648	.936	1.22	1.66
20	1183.	.0400	.080	.240	.400	.560	.720	1.04	1.36	1.84
19	1500.	.0444	.089	.267	.440	.616	.792	1.14	1.50	2.02
18	1875.	.0493	.099	.297	.493	.690	.887	1.27	1.68	2.27
17	2400.	.0543	.109	.327	.545	.760	.977	1.41	1.84	2.50
16	3000.	.0598	.120	.360	.600	.837	1.08	1.55	2.03	2.75
15	3750.	.0661	.132	.396	.660	.925	1.19	1.72	2.25	3.04
14	4800.	.0731	.146	.438	.730	1.02	1.32	1.90	2.48	3.36
13	6000.	.0810	.162	.486	.810	1.13	1.46	2.11	2.75	3.73
12	7500.	.0908	.182	.546	.910	1.27	1.63	2.36	3.09	4.18

Rule of Table.—To find the number of ampere turns obtainable from any size of wire given multiply the value of ampere turns given in table by the voltage to be used and divide this by 3.14 times the diameter of core plus the number found in vertical column which represents one-half of the number of layers considered.

The ampere turns depend only upon the voltage, the size of wire and the mean length of turns.

TABLE FOR DETERMINING MEAN LENGTH OF TURNS.

SINGLE COTTON COVERED WIRE.

B. & S.	Ampere Turns 1 Volt, 1 Inch.	Diameter S. C. C.	One-half Number of Layers in Coil.							
			2	4	6	8	10	14	18	24
40	11.4	.0071	.014	.042	.070	.098	.126	.182	.238	.327
39	14.4	.0075	.015	.045	.075	.105	.135	.195	.255	.345
38	18.2	.0080	.016	.048	.080	.112	.144	.208	.272	.368
37	22.9	.0084	.017	.051	.085	.119	.153	.221	.289	.389
36	28.9	.0090	.018	.054	.090	.126	.162	.234	.306	.430
35	36.8	.0096	.019	.057	.095	.133	.171	.247	.323	.442
34	46.1	.0100	.020	.060	.100	.140	.180	.260	.340	.460
33	58.1	.011	.022	.066	.110	.154	.198	.286	.374	.506
32	73.2	.012	.024	.072	.120	.168	.216	.312	.408	.552
31	92.4	.013	.026	.078	.130	.182	.234	.338	.442	.598
30	116.	.014	.028	.084	.140	.196	.252	.364	.474	.644
29	147.	.015	.030	.090	.150	.210	.270	.390	.510	.690
28	185.	.017	.034	.102	.170	.238	.306	.442	.578	.782
27	233.	.018	.036	.108	.180	,252	.325	.468	.612	.828
26	293.	.020	.040	.120	.200	.280	.360	.520	.680	.920
25	371.	.022	.044	.132	.220	.308	.396	.572	.748	1.01
24	461.	.024	.048	.144	.240	.336	.432	.624	.816	1.10
23	591.	.027	.054	.162	.270	.378	.486	.702	.918	1.24
22	745.	.029	.058	.174	.290	.406	.522	.754	.986	1.38
21	938.	.032	.064	.192	.320	.448	.576	.832	1.09	1.47
20	1183.	.036	.072	.216	.360	.504	.648	.936	1.23	1.66
19	1500.	.040	.080	.240	.400	.560	.720	1.04	1.36	1.84
18	1875.	.045	.090	.270	.450	.630	.810	1.17	1.53	2.06
17	2400.	.050	.100	.300	.500	.700	.900	1.30	1.70	2.29
16	3000.	.055	.110	.330	.550	.770	.990	1.43	1.87	2.54
15	3750.	.062	.124	.372	.620	.868	1.16	1.61	2.11	2.83
14	4800.	.069	.138	.414	.690	.966	1.24	1.79	2.36	3.15
13	6000.	.077	.154	.462	.770	1.08	1.39	2.00	2.62	3.52
12	7500.	.086	.172	.516	.860	1.20	1.55	2.23	2.92	3.95

Rule of Table.—To find the number of ampere turns obtainable from any size of wire given multiply the value of ampere turns given in table by the voltage to be used and divide this by 3.14 times the diameter of core plus the number found in vertical column which represents one-half of the number of layers considered.

The ampere turns depend only upon the voltage, the size of wire and the mean length of turns.

TABLE FOR DETERMINING MEAN LENGTH OF TURNS.

SINGLE SILK COVERED WIRE.

B. & S.......	Ampere Turns 1 Volt, 1 Inch.	Diameter S. S. C.......	One-half Number of Layers in Coil.							
			2	4	6	8	10	14	18	24
40	11.4	.0051	.010	.030	.050	.070	.090	.130	.170	.230
39	14.4	.0055	.011	.033	.055	.077	.099	.143	.187	.253
38	18.2	.006	.012	.036	.060	.084	.108	.156	.207	.276
37	22.9	.0064	.013	.039	.065	.090	.116	.168	.219	.297
36	28.9	.007	.014	.042	.070	.098	.126	.182	.238	.322
35	36.8	.0076	.015	.045	.076	.106	.137	.198	.258	.350
34	46.1	.008	.016	.048	.080	.112	.144	.208	.272	.368
33	58.1	.009	.018	.054	.090	.126	.162	.234	.306	.434
32	73.2	.010	.020	.060	.100	.140	.180	.260	.340	.460
31	92.4	.011	.022	.066	.110	.154	.198	.286	.374	.506
30	116.5	.012	.024	.072	.120	.168	.216	.312	.408	.552
29	146.	.013	.026	.078	.130	.182	.234	.338	.442	.598
28	185.	.015	.030	.090	.150	.210	.270	.390	.510	.690
27	233.	.016	.032	.096	.160	.224	.288	.416	.544	.736
26	293.	.018	.036	.108	.180	.252	.324	.468	.612	.828
25	371.	.020	.040	.120	.200	.280	.360	.520	.680	.920
24	461.	.022	.044	.132	.220	.308	.396	.572	.748	1.01
23	591.	.025	.050	.150	.250	.350	.450	.650	.850	1.15
22	745.	.027	.054	.162	.270	.378	.486	.702	.918	1.24
21	938.	.030	.060	.180	.300	.420	.540	.780	1.02	1.38
20	1183.	.034	.068	.204	.340	.476	.612	.884	1.16	1.56
19	1500.	.037	.075	.225	.375	.525	.675	.975	1.27	1.72
18	1875.	.042	.084	.252	.420	.588	.756	1.09	1.43	1.93
17	2400.	.047	.094	.282	.470	.658	.826	1.22	1.60	2.16
16	3000.	.053	.106	.318	.530	.742	.954	1.38	1.80	2.24
15	3750.	.059	.118	.354	.590	.826	1.06	1.53	2.00	2.73
14	4800.	.066	.132	.396	.660	.924	1.19	1.72	2.24	3.04
13	6000.	.074	.148	.444	.740	1.04	1.33	1.92	2.52	3.40
12	7500.	.083	.166	.498	.830	1.16	1.49	2.16	2.82	3.82

RULE OF TABLE.—To find the number of ampere turns obtainable from any size of wire given multiply the value of ampere turns given in table by the voltage to be used and divide this by 3.14 times the diameter of core plus the num-
the number of layers considered.
ber found in vertical column which represents one-half of

The ampere turns depend only upon the voltage, the size of wire and the mean length of turns.

TABLE FOR DETERMINING MEAN LENGTH OF TURNS.

ENAMELED WIRE.

B. & S.......	Ampere Turns 1 Volt, 1 Inch.	Diameter Enameled Wir.	One-half Number of Layers in Coil.							
			2	4	6	8	10	14	18	24
40	11.4	.0034	.007	.021	.035	.049	.063	.091	.119	.161
39	14.4	.0038	.008	.024	.040	.056	.072	.104	.136	.184
38	18.2	.0044	.009	.027	.045	.063	.081	.117	.153	.207
37	22.9	.0049	.010	.030	.050	.070	.090	.130	.170	.230
36	28.9	.0054	.011	.033	.055	.077	.099	.143	.187	.253
35	36.8	.0060	.012	.036	.060	.084	.108	.156	.204	.276
34	46.1	.0068	.014	.042	.070	.098	.126	.182	.238	.322
33	58.1	.0076	.015	.045	.075	.105	.135	.195	.255	.345
32	73.2	.0086	.017	.051	.085	.119	.153	.221	.289	.391
31	92.4	.0096	.019	.057	.095	.133	.171	.247	.323	.437
30	116.	.0107	.021	.063	.105	.141	.189	.273	.357	.483
29	147.	.0121	.024	.072	.120	.168	.216	.312	.408	.552
28	185.	.0135	.027	.081	.135	.189	.243	.351	.459	.621
27	233.	.0151	.030	.090	.150	.210	.270	.390	.510	.690
26	293.	.0169	.034	.102	.170	.238	.306	.442	.578	.782
25	371.	.0189	.038	.114	.190	.266	.342	.494	.646	.874
24	461.	.0212	.042	.126	.210	.294	.378	.546	.714	.966
23	591.	.0237	.047	.141	.235	.329	.423	.611	.799	1.08
22	745.	.0266	.053	.159	.265	.371	.477	.689	.901	1.22
21	938.	.0298	.060	.180	.300	.420	.540	.780	1.02	1.38
20	1183.	.0333	.067	.201	.335	.469	.603	.871	1.14	1.54
19	1500.	.0372	.074	.222	.370	.518	.666	.962	1.26	1.70
18	1875.	.0417	.083	.249	.415	.581	.747	1.08	1.41	1.91
17	2400.	.0468	.094	.282	.470	.658	.846	1.22	1.60	2.16
16	3000.	.0523	.105	.315	.525	.735	.945	1.36	1.78	2.41
15	3750.	.0587	.117	.351	.585	.819	1.05	1.52	1.99	2.69
14	4800.	.0658	.132	.396	.660	.924	1.19	1.72	2.24	3.01
13	6000.	.0738	.148	.444	.740	1.04	1.33	1.92	2.52	3.40
12	7500.	.0827	.165	.495	.825	1.15	1.49	2.14	2.81	3.79

Rule of Table.—To find the number of ampere turns obtainable from any size of wire given multiply the value of ampere turns given in table by the voltage to be used and divide this by 3.14 times the diameter of core plus the number found in vertical column which represents one-half of the number of layers considered.

The ampere turns depend only upon the voltage, the size of wire and the mean length of turns.

CHAPTER XII.

PLUNGER MAGNETS

In lifting magnets of the general type shown by Fig. 117 there is a very strong pull, but it is exerted through only a short distance, such as a fraction of an inch. The magnet does not lift the load through motion produced by magnetic attraction, but merely holds the load to itself while both magnet and load are raised by some mechanical power such as a winch operated by an electric motor or a steam engine.

Lifting magnets are used for handling scrap iron, pig iron, barrels of nails, and any detached articles of iron or steel. A magnet about 4½ feet in diameter using ten kilowatts of electric power may have a maximum lifting capacity of about 25 tons. However, the actual lifting ability depends on how much of the surface of parts being handled is in contact with the face of the magnet. The 25-ton magnet will lift only about 1¼ tons of pig iron in bars, because of the small areas of contact.

The lifting magnet is lowered into contact with the articles to be handled, then the current is turned on to lock the load to the magnet. To release the load from a direct current magnet, a controller puts a small reverse current through the winding in order to kill the residual magnetism. This cuts the time for releasing to about one-fifth what it would be when only turning off the current without any reversal.

Current through the winding of a plunger magnet such as shown by Fig. 118 magnetizes the plunger in such direction that the north poles of both winding and plunger are at the same end, either upper or lower, and the two south poles are at the opposite end. Then, when the plunger is out of the winding, as in the diagram, the north pole of the plunger is nearest the south pole of the winding. Since magnetic lines of force always act to make the magnetic path as short as possible, the plunger is forcibly drawn into the winding.

As the plunger just commences to enter the winding, there is practically no pull. As the plunger moves farther and farther into the winding the pull increases rapidly until, with the position shown by Fig. 118, it is approaching its maximum value. The maximum pull is realized when the plunger is about half way into the winding, and continues until the plunger is about three-fourths of the way in. Then the pull commences to drop off, and with the plunger all the way in, the force is practically the same as when at the position of Fig. 118. The strong pull at the end of the stroke results from the iron which encloses the upper end of the winding and which acts as a stop for the plunger. Without the stop there would be but little holding effect at the end of the stroke.

Instead of having the stop at the upper end of the winding, as in Fig. 118, it may extend down into the winding in the form of an iron plug. Then the plunger cannot move all the way into the winding, but only as far as the stop. The result of using this style of stop is that the pull increases at a great rate as the inner end of the plunger approaches the plug or stop. When the end of the plunger comes against the stop there is a holding effect many times greater than obtained with the construction of Fig. 118. This construction is used when the load is to be pulled through a moderate distance and then held securely in position. With a winding 12 inches long and a stop extending 2½ inches into the winding, the pull increases at a fairly steady rate until the plunger has entered to a distance of about eight inches. During the remaining 1½ inches of travel the pull increases at a rapid rate.

To obtain a somewhat greater pull at the beginning of the stroke, a more uniform increase of pull throughout the stroke, and to avoid the sudden increase of pull at the end of the stroke, the entering end of the plunger may be made conical in shape, and a corresponding cone-shaped recess made in the end of the plug. Such magnets are used chiefly for short strokes, since with a long plunger the conical end would be too small a portion of the whole length to have much effect on operation.

INDEX

Absolute unit of magnetism........................190
Air gap, effect on magnetic circuit.................196
Alternating current, generation of...............4, 164
Alternating current armatures......................165
Ampere turns 23, 190
    to produce a given flux........................194
Arc machines, armature winding................... 68
Armature bearings 37
    calculations 148
    insulation 104, 111
    reaction 9
    troubles 140
Armatures, mechanical construction............... 33

Balancing of armatures.......................... 33
Bar wound armature.............................132
Barrel winding 131
Binding wires 115
Bipolar drum winding......................71, 75, 76
    short chord 81
    two layers 83, 86, 87
Bipolar ring winding............................ 59
    duplex 64
Brush arc armature.............................. 68

Brushes, arrangement of 138
    proper location of 16
    size of 19, 138

Calculation of armature 148
    of magnet winding 189
Carbon brushes 138
Cast iron, properties of 194
Closed coil winding 53
Coils, wrong connection, test for 140
Commutation, sparkless 16
Commutator construction 134
    office of 5
Connections for armatures 44
Cross magnetization 12
Current allowed in armature wire 153
    generation 1

Demagnetizing effect of armature current .. 14, 83, 90, 93
    turns 15
Direction of flow of induced current 2
Drum armatures, practical winding 118
Drum winding, bipolar 71, 75, 76
    bipolar, short chord 81
    bipolar, two layer 83, 86, 87
    multipolar, four brushes 90
    multipolar, two brushes 97
Drum wound armatures 71

Duplex winding 66

Eddy currents in armature...................... 30
Electro-magnets. (See magnets.)
Element of winding............................ 51
Evolute winding 131

Field of force 21
Field resistance 149
Fleming's rule 2
Force, lines of 21
Former coils 126
Foucault currents 29

Gramme ring armature 54
Grounded coils, test for.....................144

Heating coils 231
Heating of armature wires....................154
    of electro-magnets 199, 204
Helix 190
Hysterisis 31

Inductance of armature coils................. 18
Insulation of commutator segments............136

Laminations of armature..................30, 38
Lap winding 49, 67, 92

Leakage of lines of force........................148
Lines of force, direction of...................... 2
Long connection, armature....................... 67

Machine winding 126
Magnet, lifting 218
  long range 220
  quick action 221
  and condenser 218
  coil, for fixed current.......................209
  insulation of 231
  retardation 222
Magnet formulas 212
Magnet types 213
Magnet winding, calculation of...................189
  joints 229
  non-inductive 230
  table of constants 239
  Varleys 226
Magnetic circuit 21
  ring wound bipolar armature.................. 54
  dynamo 28
Magnetic flux 24
  table of 194
Magnetic induction, curves of 26
Magnetic traction 195
Magnetization of iron 192
Magneto-motive force......................... 22

Magnets, counting machine 225
    direction of winding........................214
    general facts concerning........................233
    general formulas 237
Magnets, practical points 222
    sparking 216
    thickness of insulation 236
    winding machine 226
Mechanical construction of armature.............. 33
Motor, principle of operation...................... 9
Multipolar drum winding........................90, 97
    ring winding 59, 60, 61, 67

Neutral point, location of in dynamo.............. 11
    location of in motor........................ 13

Oil shields 37
Open circuit, test for in armatures................145
Open coil ring armature........................ 68
    winding 53

Parallel circuits through armature................ 44
Permeability 24
    table of 194
Pitch of armature conductors........................ 50
Polarity of armature 11
    of helix 190

Radiating surface of armatures....................154

Reaction of armature........................... 5
Regulation of dynamo...........................140
Reluctance 24, 27
Ring armature, practical winding...............103
Ring winding, bipolar 59
    bipolar, duplex 64
    multipolar 60, 61
    multipolar, two brushes.................... 67
    open coil 68
Ring wound armature 54

Saturation of iron............................ 25
Shafts for armatures.......................... 36
Shifting of brushes, dynamos...............12, 20
    motor 13
Short circuit in armature, teat for............146
Short connection, armature 67
Single phase armatures 167
Slotted armature, arrangement of conductors.97, 121, 158
Sparking of commutator........................ 16
    of arc machine............................. 70
Speed, calculation of 151
Squirrel cage armature.........................188
Staggering of brushes..........................138
Strength of field...............................151

Table, carrying capacity of armature wires.....155, 156
    carrying capacity of German silver wire........250

- copper wire 246
- diameters and squares........................249
- fusing of wires........................252
- insulated copper wire........................248
- permeability 194
- properties of electro-magnets.............194, 202

Table, square roots 242
- wire and sheet metal gauges..................251

Taping armature coils 133

Testing of armatures 140

Three phase armatures........................179

Traction of electro-magnets........................195

Triplex winding 66

Trouble armature 140

Two phase armatures 175

Ventilation of armature 46

Volt, production of........................ 1

Volts, generation by armature....................151

Wave winding, drum armatures................67, 69
- ring armatures 50

Winding, former coils 126
- method of 104

Wires per slot, armature........................151

Wrought iron, properties of........................194

ARMATURE
AND
MAGNET
WINDING

HORSTMANN
AND
TOUSLEY

DRAKE

Radio—Electricity

Drake's Cyclopedia of Radio and Electronics. Buckram	$5.00
Drake's Electrical and Radio Dictionary. Cloth	2.50
Practical Electricity and House Wiring. Cloth	1.50
House Wiring Made Easy. Cloth	1.00
Armature and Magnet Winding. Cloth	1.50

Machine Shop—Sheet Metal

Drake's Basic Machine Shop Practice. Cloth	$3.00
Sheet Metal Workers' Manual. Cloth	2.00
Aircraft Sheet Metal Construction and Repairs	1.50
Electric and Oxy-Acetylene Welding. Cloth	1.50

Diesel-Steam Engineering

Diesel Engines and Diesel Electric Power. Cloth	$2.50
Ques. & Ans. for Marine and Stationary Engineers	2.00
Steam Boilers—Care and Operation. Cloth	2.00

Aviation

Aircraft Powerplant Manual. Cloth	$4.00
Aircraft Electrical and Ignition Systems. Cloth	2.00
Win Your Wings—Book I. Cloth	3.00
Win Your Wings—Book II. Cloth	3.00
Aviation from the Ground Up. Cloth	3.00

Commercial Art—Cartooning

"101 Roughs"—A Handbook of Advertising Layout	$3.00
Layouts for Advertising. Cloth	2.00
Studio Handbook—Letter and Design. Cloth	3.00
Silk Screen Methods of Reproduction. Cloth	3.00
Figure Drawing from Life. Paper	1.00
The Amateur Artist. Cloth	1.50
Lettering—Modern and Foreign. Cloth	3.50
Modern Lettering and Design. Paper	1.00
How to Draw Funny Pictures. Cloth	2.00
The Art of Caricaturing. Cloth	2.00
Modern Illustration. Cloth	2.00
Practical Color Management. Cloth	1.50

Naval Training

Handbook of the Nautical Road. Cloth	$3.00
Rules of the Road. Cloth	2.00

Miscellaneous

Drake's Spanish Grammar. Cloth	$1.50
Finger Prints Simplified. Cloth	1.50

ARMATURE and MAGNET WINDING

HORSTMANN and TOUSLEY

DRAKE